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A new large-scale, high-resolution,  
multicolor software display concept

Joseph G. Logan

Applied Energy Sciences, Inc.  
3716 South Hope Street, Room 223  
Los Angeles, California 90007

March 1985

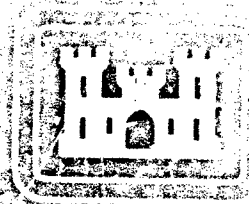
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Progress in CRT display technology has been limited. Consequently, new technologies are being examined (e.g., solid-state, "flat-panel" displays) that might be applicable for a large-scale, high-resolution, multicolor software display.  In this proposal, a "new" approach to very large screen display technology is suggested, based on the unique piezoelectric properties of stretched polyvinylidene fluoride films. The objective of this Phase I program is to demonstrate		

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20. ABSTRACT continued.

that individual picture elements can be developed, yielding the necessary gray-scale range, to form the basis for large-screen display and that these elements can also easily be modified to incorporate full-color display.

This report provides a summary of the activities carried out during the six-month Phase I program to demonstrate that the use of simple bimorph elements to modulate light beams provides a very simple technique for the development of large, flat-screen display systems. The construction of simple prototype display elements to demonstrate the feasibility of the approach is also described. The potential for the development of inexpensive display systems is suggested:

in particular, it is shown that the U.S. Army Engineer Topographic Laboratories' requirement for a large-scale, high-resolution, multicolor software display to proof and display maps and charts can be satisfied using this approach.

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## I. SUMMARY

On August 20, 1984, a contract was signed by Applied Energy Sciences, Inc. with the Department of the Army's Humphreys Engineer Center Support Activity to undertake a project which was solicited under the FY83 Small Business Innovation Research Program (SBIR).

In the proposal, a "new" approach to very large screen display technology was suggested based on the unique piezoelectric properties of stretched polyvinylidene fluoride (PVDF) films. A basic objective of the Phase I program was to demonstrate that individual picture elements can be developed, yielding the necessary gray-scale range, to form the basis for large-screen display and that these elements can easily be modified to incorporate full-color display. This basic objective was successfully accomplished.

In the past several years, extensive studies have been conducted to investigate the properties and explore the applications of PVDF piezoelectric polymer films. The piezoelectricity of this material is comparable to that of crystalline solids. A major advantage is that the material is easy to handle since it is not brittle, and it can easily be formed in large-area thin films. Voltage-excited bimorphs using PVDF film produce a large amplitude bending motion that is not equalled by any other piezoelectric device. While devices based on the use of PVDF films have not yet been commercialized on a large scale, the interest in such devices is progressively increasing. The studies described in this report offer the opportunity for large-scale commercialization of these promising films.

A primary goal of the research and development in this Phase I program and the proposed development in the following Phase II program is the demonstration that low-cost, low-power, easily fabricated, "flat," large-screen displays can be constructed utilizing this technology. The technology application uses the same basic electronic components that have been developed for liquid crystal display (LCD) and electroluminescent (EL) display devices.

The motivation for the investigation was the need to explore new techniques for the development of large-scale displays to satisfy the U.S. Army Engineering Topographic Laboratories requirement for a large-scale, high-resolution, multicolor software display to proof and display maps and charts. The studies conducted in the Phase I program have demonstrated that this development can be successfully accomplished and that large-scale, multicolor software displays can be constructed to satisfy this Army requirement.

In accordance with the requirement of Army Contract DACW 72-84-C-0013, the following report is submitted describing this program carried out by Applied Energy Sciences, Inc. in the fulfillment of this Contract for the period 20 August 1984 to 20 February 1985.

The activities summarized in this report include:

1. A review of the characteristics of piezoelectric PVDF films and preparation techniques;
2. Review of the theoretical performance of bimorph elements constructed using PVDF films;
3. The experimental studies by Applied Energy Sciences of the performance of two- and three-electrode bimorphs;
4. The design of display configurations utilizing bimorphs as modulators of optical elements of a display;
5. The construction and performance of prototype display units utilizing bimorph elements;
6. The design and construction of an 8x8 matrix address system to operate a 64-element display configuration;
7. The design of configurations to satisfy the Army requirement;
8. Preliminary market studies of the potential for large, flat-panel display devices based on the use of mechanical optical valves constructed with PVDF bimorph valve elements.

## II. FOREWORD

For over a decade, a major part of the activities in research and development for display devices in this country and in Japan has been directed toward a single target: flat-panel displays. Although electron beam scan technology (cathode-ray technology) has dominated the field of display devices since the early unsuccessful attempts to devise mechanical image forming systems, the use of an integral system to generate the image element illumination, the gray-scale requirements (modulation), the necessary scanning rates, and the chromatic scale requirements has many drawbacks. These drawbacks result from the physical limitations that make difficult the scaling to large display systems and the requirements for high voltage and high power. The use of projection system techniques does not result in a completely satisfactory alternative.

The concept of a flat cathode-ray tube is as old as television itself. Papers published in the 1950's and 1960's reported on early attempts at tube design. These early efforts sparked interest among the military, which envisioned command and control and instrument panel applications, as well as among the consumer who envisioned television sets that could be hung from a wall. Flat TV (CRT) research has yielded small screen systems. Large flat-panel display devices are now, however, being successfully developed based on recent solid state technology. These devices are somewhat limited and expensive. A typical example is indicated in Exhibit A. Flat-panel display systems with the capacity for display exhibited by the electron-beam-scan-technology-based CRT have not as yet been developed.

Recently, however, the rapid advances in the field of ferroelectric polymers have suggested that technologies based on the use of piezoelectric thin film materials might yield new types of flat-panel display systems with very low energy consumption that could exceed the current capabilities of display systems based on electron beam scan technology and prove to be superior to other recent developments in flat-panel display technologies (e.g. Exhibit A). The new developments are based on ferroelectric, thin-film, "mechanical" image-forming systems.

Piezoelectric polymer research is a relatively new activity. The roots of piezoelectric polymer research extend back to the 1920's, when scientists discovered that certain organic materials could be cooled in a electric field to yield solids with piezoelectric and pyroelectric activity. Most of the subsequent work focused on biological polymers until a short note published in 1969 reported larger-than-usual piezoelectric activity in polyvinylidene fluoride. This report sparked considerable interest in using PVDF in such piezoelectric and pyroelectric devices as speakers, hydrophones, and electromagnetic radiation detectors.

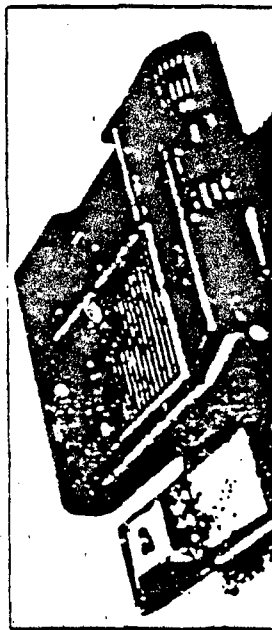
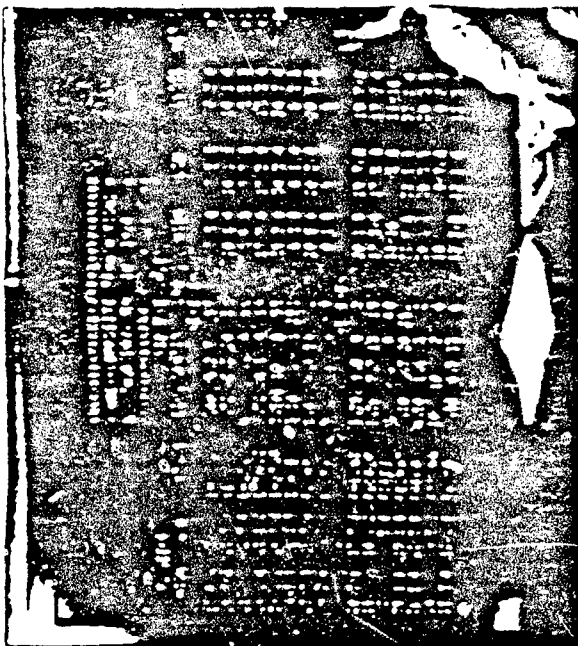
EXHIBIT II-A

## What's New in Electronics

BY WILLIAM J. HARRING

### Big display

It's a computer display, but the four-in-thick, 44-by-70-in. panel shows 24 rows of 80 one-in.-high characters that are viewable from 60 ft. away. The Plasma Terminal Module is made by Quantum Electronics, Box 6AAA, Lewistown, Pa. 17044. The price matches its size: \$35,000.



From: Popular Science - February 1985.

While engineering applications were being explored, a few groups of scientists sought to understand the molecular basis of piezoelectricity in polymers. Some researchers examined solid state models of charge injection and storage. Others investigated the behavior of molecular dipoles in one or more of the various crystal and amorphous phases common to PVDF. The subtlety of molecular orientation effects in early low-activity samples delayed the experimental confirmation of speculative reports of ferroelectricity in PVDF until the latter half of the 1970's when compelling evidence from x-rays and infrared studies demonstrated electric-field induced crystallographic re-orientation and phase changes. Today, workers in the field are essentially united in the view that PVDF is a ferroelectric with its piezoelectric/pyroelectricity traceable to the electric moment contained in the polar crystal phases of the polymer.

In the past several years, extensive studies have been conducted to investigate properties and explore the applications of PVDF piezoelectric polymer films. The piezoelectricity of this material is fairly comparable to that of crystalline solids. The material is easy to handle since it is not brittle, and it is relatively easy to form in large area thin films. Voltage-excited bimorphs using PVDF film produce a large amplitude bending motion that is not equalled by any other piezoelectric device.

Interest in applications based on piezoelectric characteristics is now developing rapidly and today the outlook for continuing and steady developments of piezoelectric polymer devices appears excellent. Producers are increasing the availability of piezoelectric polymer film. Improved processing techniques are increasing molecular orientation and producing good quality film in thicker (of interest for hydrophones) and thinner (of interest for pyroelectric applications) sizes. Properties are being modified with the use of copolymers, and the unique advantage of polymers for many applications is now becoming apparent. Most important, the sophistication of scientific research on these materials is increasing rapidly, and the integration of this polymer work with the classical field of ferroelectricity is finally opening up the field to a broader range of researchers and experimentors.

The investigations to be described in the following pages are focused on the performance of simple bimorph structures functioning as optical valves for flat panel display system applications. The potential of the application suggests that this new ferroelectric technology offers, for the first time, the promise of the successful development of a large flat panel "mechanical" image forming system.

The studies described in this report were carried out in the Small Business Innovation Center of the Western Research Application Center (WESRAC) of the University of Southern California. This Center, designed to provide support to very small research and development organizations in the private sector interested in new technology developments, is located in the Research Annex of the University of Southern California.

### III. PREFACE

This work was accomplished under the technical direction of Mr. A.J. Bondurant, Jr., and Mr. M.C. Straub of the U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia. The Humphreys Engineer Center Support Activity, Fort Belvoir, Virginia, administered the contract, DACW72-84-C-0013.

The PVDF films used in the investigations were supplied by the Pennwalt Corporation, King of Prussia, Pennsylvania, and the Yarsley Technical Centre, Surrey, England. Acknowledgement is also made for the data contained in the technical manuals supplied by these agencies.

The review of bimorph theory presented in this report (Appendix A) was based primarily on the theoretical studies carried out by M.A. Marcus of the Research Laboratories of Eastman Kodak and M. Toda of the RCA Research Laboratories, Tokyo. The numerous papers published by M. Toda also provided much valuable information on the practical techniques for preparation and the applications of these films.

When the Small Business Innovation Program (SBIR) was initiated, WESRAC was in the process of formulating plans to develop an Innovation Center to support new small business organizations and selected entrepreneurs in applied research and development activities in new technology fields. The Innovation Center concept was expanded to include an "Incubator Facility" for SBIR Phase I award winners who could be classified as "new" business developments in need of support facilities at a modest cost.

Applied Energy Sciences, Inc. was the first small business R & D organization invited to become an occupant of the Incubator Facility when its SBIR award was received.

Applied Energy Sciences is pleased to acknowledge the support and assistance provided by WESRAC through its many support services that made a substantial contribution to the success of the program described in the following pages. In particular, the support provided by Mr. Radford G. King, the Executive Director of WESRAC, is acknowledged.

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#### IV. SBIR PHASE I PROGRAM

##### 1. INTRODUCTION

###### a. Background

Since its discovery, piezoelectricity constitutes a classical domain of the physics of crystalline materials. The earliest and most prominent example of piezoelectric crystals is quartz, which still holds a unique position owing to its wide spectrum of applications ranging from underwater echo-sounding to highly stable frequency filters. The immense technical importance of the piezoelectric effect has been a great stimulant for the search of new piezoelectric materials and, along this line, polycrystalline ceramics with the largest piezoelectric coefficients observed so far have been developed.<sup>1,2</sup>

Today a new area of piezoelectric substances, which are by no means perfect crystals, has been brought forward by the discovery of the piezoelectric effect in polymers. These materials, owing to their flexibility and capability of being utilized in large sizes, offer new applications which could not have been realized before with brittle and expensive crystals. The most attractive of these polymers now and the one this paper is concerned with is polyvinylidene fluoride (PVDF) which has already manifested its future potential use in a number of exciting devices such as piezoelectric loudspeakers or fast pyroelectric detectors.<sup>3-9</sup>

The developments in this new field are based mainly on the pioneering work of Fukada and co-workers,<sup>10-13</sup> who investigated the piezoelectric properties of a number of biological macromolecules. They found that rolled films of polypeptides and even samples prepared from substances like bone or tendon develop surface charges when stressed in the film plane. Surprisingly, piezoelectric constants as large as  $5 \times 10^{-8}$  cgsesu, comparable to crystalline quartz, have been obtained without any previous electrical treatment.<sup>13</sup> However, the effect only occurs when a shear stress is applied to the sample, i.e., only the piezoelectric shear coefficients  $d_{14}$  and  $d_{25}$  are observed. This special symmetry of the piezoelectric tensor seems to be a common feature of all piezoelectric biopolymers investigated so far and is attributed by several authors to the uniaxial texture of the material induced by rolling or simply by growth.<sup>13,14</sup> Most interesting, the idea of electrically stimulating the growth of biological tissue (or healing of bone fractures) was born out of these early experiments and several clinical tests have now already been carried out.<sup>15-16</sup>

On a larger scale, however, the general interest in piezoelectric polymers was stimulated by the important observations obtained with especially one synthetic polymer, polyvinylidene fluoride.

In 1969, Kawai could show<sup>17</sup> that stretched films of PVDF when first heated to 90 C and subsequently cooled down to room temperature in a constant dc electric field (of about 0.3MV/cm) proved to be three to five times more strongly piezoelectric than crystalline quartz. Other polymers, however, such as polycarbonate or polyvinylchloride, after being polarized under the same conditions, did not show any comparable effect. Subsequently, Fukada and Sakurai demonstrated<sup>18</sup> that, in contrast to the piezoelectricity in biopolymers, PVDF shows

the largest piezoelectric strain coefficient in the initial drawing direction ( $d_{31} \gg d_{32}$ ). Further experiments on the electromechanical coupling factor made clear, however, that the piezoelectric effect normal to the PVDF-film plane, i.e., parallel to the direction of the poling field, is even stronger than the transverse effect ( $K_{33} \approx 20\%$ ).<sup>19</sup> In fact, this observed anisotropy can be satisfactorily explained by the high Poisson ratio of the oriented texture indicating that the anisotropy of the piezoelectric effect in PVDF might simply be due to the anisotropic elastic constants of the drawn polymer film.<sup>20</sup>

Both vibrational modes of piezoelectric PVDF films have already been utilized for acoustical applications: ultrasonic waves up to microwave frequencies have been generated with thin PVDF transducers,<sup>21-23</sup> and in the audio range, a new type of loudspeaker has been designed using the transverse piezoelectric effect of a mechanically biased PVDF membrane.<sup>3-5</sup>

Moreover, hysteresis effects similar to crystalline ferroelectrics have been observed for polarized PVDF films,<sup>24</sup> suggesting its use as a new material for switching or storage purposes.

But also concerning its pyroelectric properties, PVDF shows an outstanding behavior: whereas ordinary thermoelectrets lose their polarization charge completely, PVDF carries a stable and reversible polarization of about  $0.1 \mu\text{C}/\text{cm}^2$  which persists even after several heating cycles<sup>25-26</sup> as it is usually observed for pyroelectric crystals. As a consequence, PVDF films were successfully used as pyroelectric detectors and rise times of the order of nanoseconds have been observed.<sup>6-9,27</sup>

In spite of the large progress in the field of applications, our basic understanding of the origin of the piezoelectric effect in PVDF is relatively poor. There is still no clear evidence if the piezoelectric observations are caused by a bulk or a surface property of the polymeric solid. Although most of the previous authors assumed that the piezoelectricity of PVDF is an inherent property of the crystalline regions of the polymer,<sup>17-19,28</sup> i.e., owing to a volume polarization, recent experiments by Murayama<sup>29,30</sup> and Pfister et al.<sup>25</sup> indicate that charge injection from the electrodes and their subsequent trapping in the crystalline regions might be responsible for the polymers polarization.

Furthermore, the different contributions of the crystalline and amorphous parts to the polarization of PVDF are still unclear. Even though the piezoelectric constant  $d_{31}$  increases with increasing content of the crystalline polar  $\beta$  form<sup>30</sup> a strong piezoelectric effect ( $K_{33} \approx 20\%$ ) is still observed when mainly (90%) of the nonpolar  $\alpha$  form is present.<sup>19-21,26</sup> It was further demonstrated<sup>31</sup> that an enormous polarization of several  $\mu\text{C}/\text{cm}^2$  can be induced in PVDF by corona charging even at room temperature. Below the glass transition temperature ( $T_g = -40^\circ\text{C}$ ), however, the polarization decreases significantly indicating clearly the importance of the amorphous regions in the build up of the polymers polarization.

There is evidence that the strong piezoelectricity of PVDF originates at the positive metal electrode, and that it is not at all homogeneous across the volume of the sample.<sup>1</sup> Experiments by Sussner and Dransfeld have indicated that the polarization of PVDF is strong only at the interface between the polymer and the positive electrode. Apparently this surface polarization develops in time during the poling process indicating that neither a bulk conduction nor a dipolar

alignment in the crystalline phase are the basic mechanism for the strong polarization of PVDF. The effect of poling can be determined using a number of different techniques. The piezoelectric effect of PVDF can be detected either by an optical modulation technique or simply by using the films as ultrasonic transducers in the conventional pulse-echo method.<sup>36</sup> Investigators<sup>17,28,29,30</sup> have measured the transverse piezoelectric effect ( $d_{31}$ ) by applying a sinusoidal stress in the film plane, as well as the inverse effect normal to the film plane ( $e_{33}$ ) by exciting the PVDF foils piezoelectrically in their thickness vibration.<sup>1</sup>

#### b. Properties of PVDF Piezoelectric Films

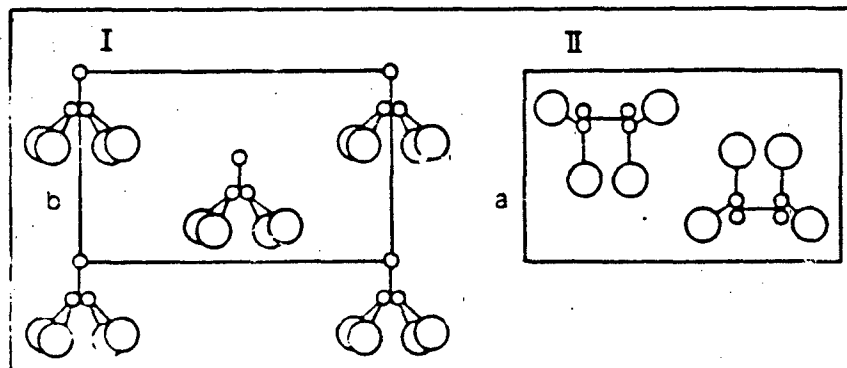
PVDF is a long-chain, semicrystalline polymer having the repeat unit  $(CH_2-CF_2)$ .<sup>1-4</sup> It is approximately 55% crystalline and has a molecular weight of typically  $4 \times 10^5$ . Four crystalline forms are known<sup>(4)</sup> and are designated forms I and II, III and IIP or  $\beta$ ,  $\alpha$ ,  $\gamma$  and  $\alpha\beta$ , respectively. The most common forms are the polar form I and the electrically inactive form II. Commercial bulk polymer consists of form II material. For high degrees of piezoelectric activity, a significant amount of oriented polar form I crystalline material is needed.

The polymer chain of form I material has a planar, zigzag, all-trans conformation. The dipoles are oriented normal to the polymer chain axis and are parallel to each other. This form is not centrosymmetric and is thus intrinsically piezoelectric (Fig. 1 (I))<sup>(5-6)</sup>. By contrast, form II has a trans-gauche-trans-gauche '(TGTG') structure and, although it has a dipole moment normal to the chain axis, the molecular chains pack such that their dipoles are in an antiparallel array, therefore a non-polar, centro symmetric unit cell results (Fig. 1 (II)).

The degrees of piezoelectricity of a sample will depend on the degree to which the dipoles can be made parallel to one another. The only commonly used way of doing this is to produce oriented sheet material and apply a high potential across it; details of such approaches are described later. Most of the foils so produced consist of a crystalline and an amorphous phase. The two phases differ in their dielectric and elastic properties. The material is polarized, with the polarization consisting of aligned dipolar chains. There will be polarization zones with real charges at their boundaries. The piezoelectricity or pyroelectricity in such a material may be due to several effects:

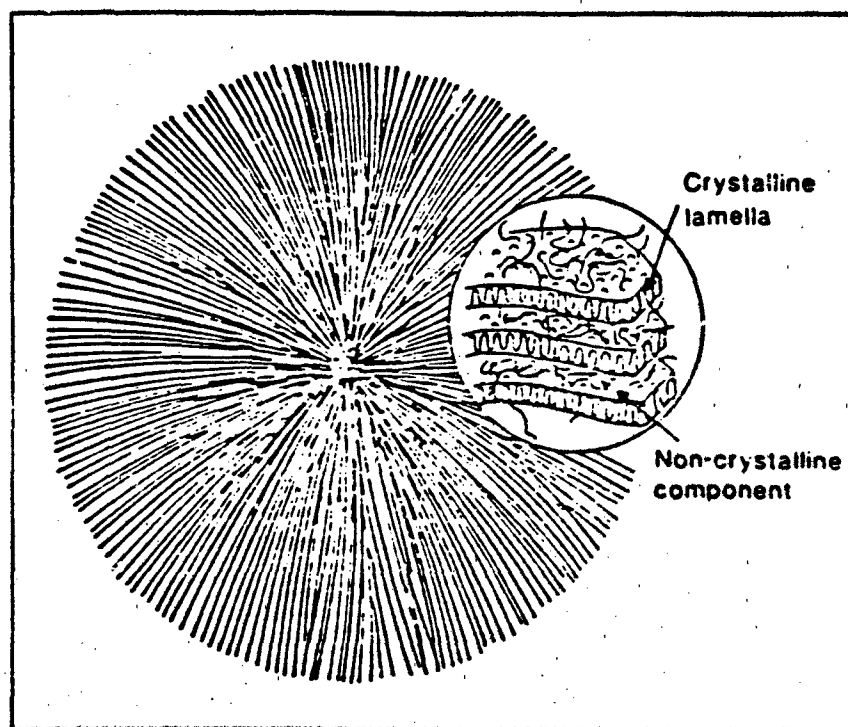
- (a) When the material is strained or heated, the dielectric constants of the crystalline and amorphous parts may alter differently. This yields an electrostrictive effect.
- (b) the elastic constants of the crystalline and amorphous parts may be different. This yields a piezoelectric effect.
- (c) the crystalline parts have an intrinsic piezoelectricity and pyroelectricity as in quartz.

It is probable that the response of PVDF is mainly due to effect (c) but research into the mechanism of piezoelectricity and the enhancement of activity by new forming and poling processes and synthetic methods is still required.



Crystalline structure of forms I ( $\beta$ ) and II ( $\alpha$ ) of PVDF projected on to the a-b plane of the unit cell. Fluorine atoms are shown as large circles, carbon atoms as small circles and hydrogen atoms are omitted. After Sessler.<sup>(2)</sup>

FIGURE IV-1



A schematic diagram of the spherulitic structure of semicrystalline PVDF. Platelets grow radially and the polymer chains are approximately normal to the plane of the platelet. After Broadhurst and Davis.<sup>(25)</sup>

FIGURE IV-2

### c. Preparation Techniques

The raw material of poly(vinylidene fluoride) is  $\text{CH}_2=\text{CF}_2$  named 1,1-difluoroethylene or vinylidene fluoride. In the abbreviation used for the polymer, the "d" is inserted to distinguish between the above material and the singly-fluorinated polymer, poly(vinyl fluoride), PVF. Other authors use the abbreviation  $\text{PVF}_2$  in place of PVDF. The piezoelectric activity of fluorinated polymers depends on the form and degree of crystallinity and on the orientation of the C-F bonds. The distinct forms recognised include those shown in Table 1.

TABLE IV-1

Name of form		Polar	Prime Preparation Method
Letter	Number		
$\alpha$	II	No	Crystallisation from melt
$\alpha_p$	IIp	Yes	Pole $\alpha$ form
$\beta$	I	Yes	Stretch foil ( $\alpha$ )
$\delta$	III	Yes	Solution crystallisation

Forms of poly(vinylidene fluoride).

PVDF is prepared in bulk by a process similar to that used for high-density polyethylene. A suspension of vinylidene fluoride, the liquid monomer, is heated with peroxide catalysts in a pressure reactor at 60-80 °C. The polymerised particles are filtered, washed and dried; stabilizers and antioxidants are added and the powder is granulated.

Because the polymer has alternating hydrogen and fluorine atoms, PVDF has better processing characteristics than other fluorocarbon polymers (for example, P.T.F.E., F.E.P. and polychlorofluoroethylene). Applications of the moulded plastic include chemical piping and reactors, valves, pumps, electrical insulation in aircraft and heat-shrinkable insulating tubing for electronics, resistors and diodes. Because of the good process characteristics, robust and defect-free foils of thickness less than 10 micrometres (0.0004") can be made economically by melt extrusion, either from a slot die or by the blown-film technique. On solidifying after extrusion, a spherulitic semicrystalline structure much like polyethylene develops (Fig. 2).

PVDF may be extruded using the blown film technique or from a slot die. Then, when melt-extruded form II PVDF sheet is uniaxially stretched typically at draw ratios of 3-5:1 and at temperatures up to 150°C, the material recrystallises predominantly as form I polymorph. Drawn PVDF film consists of parallel, crystalline, folded lamellae within the amorphous phase and between which are

less ordered polymer chains. Generally, increasing the draw ratio gives rise to an increase in total birefringence and form I crystalline content whilst increasing temperature decreases the form I crystalline content. Increasing degrees of biaxial stretch ( $\rightarrow 1 : 1$ ) lowers birefringence, form I crystalline content and the ultimate piezoelectric response whilst the mechanical properties of the film are improved.

After stretching, the dipoles in the crystal regions are still randomly oriented. "Poling" by means of a high field, applied normal to the surface of the material, is required to give practical levels of piezoelectric response.

One common method of performing the polarisation of the polymer film is to subject the electroded film to a field of  $0.5-0.8 \text{ MV cm}^{-1}$  at, for example  $100^\circ\text{C}$  for 1 hour. Subsequent cooling to room temperature in the presence of the field stabilises the polar alignment giving a virtually permanent polarisation. The technique is referred to as thermopoling.

Alternatively, a film electroded on one side (or not at all) is subjected to a corona discharge field of, for example,  $2.5 \text{ MV cm}^{-1}$  at room temperature or elevated temperature up to about  $70^\circ\text{C}$ . (Fig. 3). Corona discharge poling (e.g. from an array of needle electrodes) is the more convenient method since very much shorter times (seconds) are required to achieve comparable values of piezoelectric activity and it may be performed continuously. The high internal field in the film volume created by a charge build-up on the surface is sufficient to align the dipoles at room temperature.

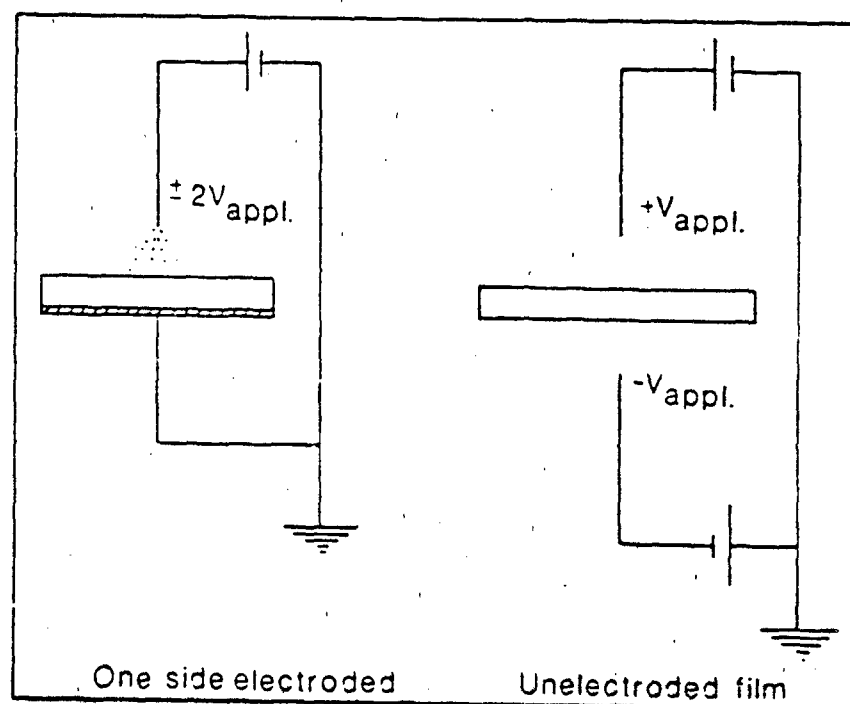
In corona poling, increasing poling temperature for a given field results in an increase in piezoelectric response (Fig. 4) up to temperatures of about  $80^\circ\text{C}$  where the response may then decline. At a given temperature, polarisation, and hence piezoelectric response, increases with applied field until a saturation condition is achieved (Fig. 5).

Corona poling, besides effecting dipolar orientation, also results in a conversion of the form II unit cell to the polar form IIP intermediate and eventually causes form II  $\rightarrow$  I conversion.

It has been suggested<sup>(7,8)</sup> that, at lower poling fields, the piezoelectricity in PVDF may arise from dipolar orientations of both form I crystallites and form IIP crystallites. Above  $2.5 \text{ MV cm}^{-1}$ , enhanced piezoelectric activity occurs as a result of the eventual conversion of form IIP and another intermediate polar phase to form I, and is entirely due to the dipolar orientation of form I type crystallites.

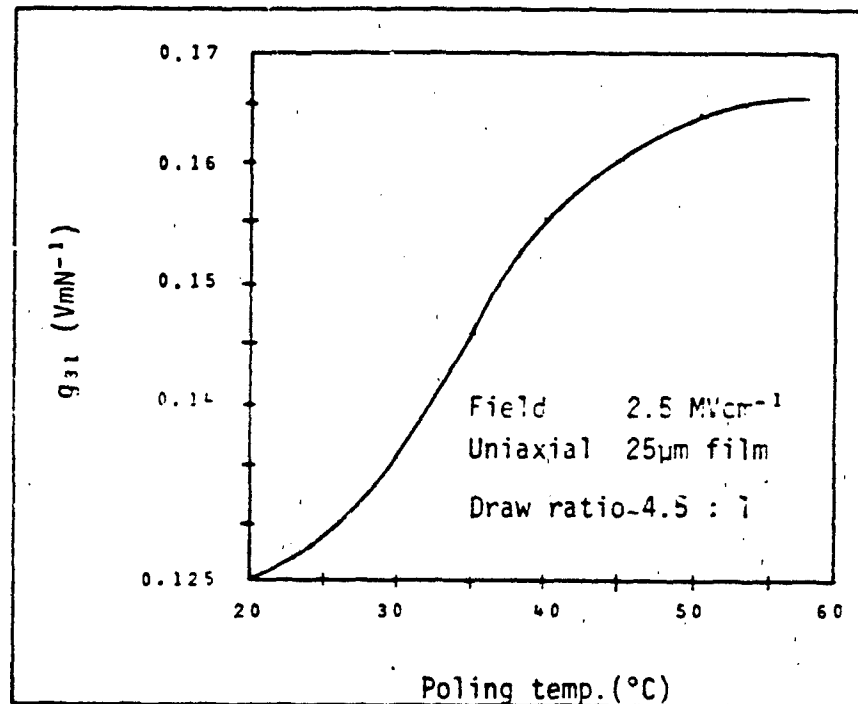
Piezoelectric coefficients are reportedly doubled when the corona poling and stretching are performed simultaneously<sup>(9)</sup>. Dipole orientation is thought to proceed very readily and remain more stable when the necking region is subjected to a corona discharge field.

Metallisation of the two surfaces may be performed using any of the standard methods: thermal or electron beam evaporation, sputtering or electroless deposition. Patterns of electrodes can be produced by masking and etching. Common

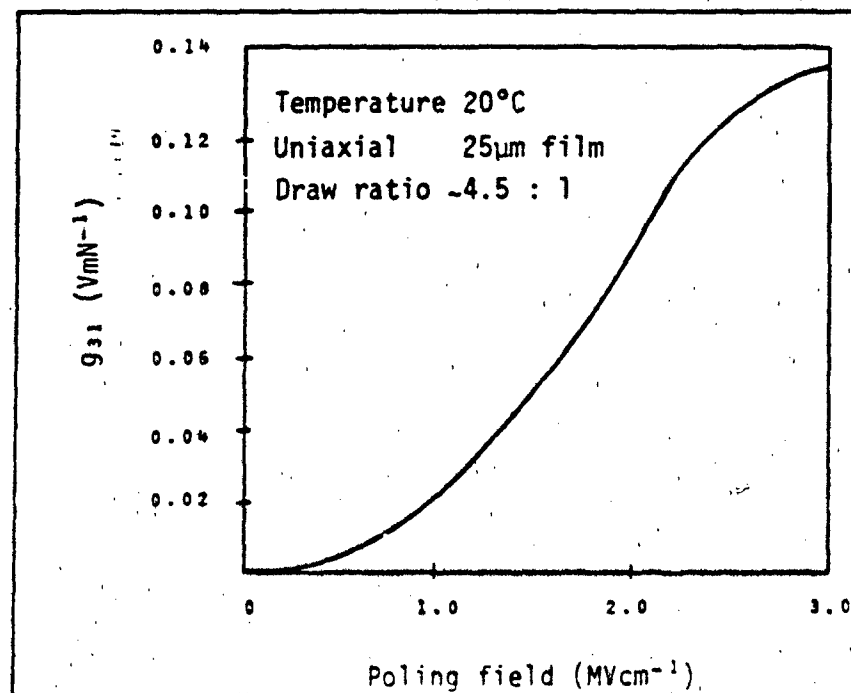


Corona discharge poling.

FIGURE IV-3



Piezoelectric constant of PVDF as a function of poling temperature.  
FIGURE IV-4



Piezoelectric constant of PVDF as a function of poling field.  
FIGURE IV-5

electrode materials are aluminium and nickel (deposited to give sheet resistances of typically 2 ohms/square) but most other unreactive metals and alloys can be employed, e.g. gold, chromium-gold, nickel-vanadium, zinc, titanium and stainless steel. The selection of a metal will generally depend on the nature of the device and its environment but it will normally be required to have one or more of the following:

- (i) acceptable adhesion to PVDF,
- (ii) corrosion resistance,
- (iii) fretting resistance, and
- (iv) ease of making electrical contact.

Adhesion and corrosion resistance are of particular importance. Underwater applications, for example, require long-term corrosion resistance and in mechanical transducers, where the metal-polymer interface can be highly stressed, good adhesion is essential. In certain driven applications it has been known for electrodes to be 'blown' off.

In films prepared by Yarsley Technical Centre there appears to be very little effect of ageing on the piezoelectric constants even after 1000 hours at 70°C and shrinkage is in the region of 5%. Life tests are continuing at Fulmer. At higher temperatures, an initial degradation occurs, but a stable residue of activity is left. This suggests that, where extra stability is required, one may obtain such stability by ageing at a temperature some degrees higher than the service temperature. Choice of manufacturing technique appears to be important, since other commercial films show larger degradation values than those given for Yarsley film. Pantelis<sup>(10)</sup> performed long-term ageing experiments on PVDF at 68°C in dry and humid conditions. After an early drop, the piezoelectric constant remained steady for 1½ years in both conditions. Pantelis also found that changes of piezoelectric constant appeared to be associated with shrinkage which, in turn, was a result of thermo-mechanical history during manufacture.

Prolonged high-temperature annealing of any form of PVDF tends to produce the  $\gamma$  form. At medium temperatures, depoling of the  $\beta$  form also probably occurs. A Yarsley film heated for 100 minutes at 150°C produced a degradation of 65%; for 120°C it was 30%; and for 90°C it was 9%. Corresponding shrinkages were 19, 8 and 4 percent.

The pronounced piezoelectric effect in poly(vinylidene fluoride) (PVDF) was first reported in 1968 by Kawai<sup>(11)</sup> and Fukada<sup>(12)</sup>. The piezoelectric and pyroelectric responses of PVDF are the highest known for any homopolymer and this is partly related to its high dielectric constant. The mechanism for its piezoelectricity is thought to be a ferroelectric-like response based on the net dipolar alignment of the highly polar carbon-fluorine bonds in form I PVDF.

When a sample of piezoelectric material is stressed, a polarization,  $P$ , occurs in the molecules as the bond angles are altered by the stress. When parallel-plate electrodes are fixed across the sample, some component of that polarization appears across those electrodes as a field,  $E$ , resulting in a voltage,  $V$ , and as a charge on the surface of the polymer. The charge can be measured

if the electrodes are connected by a low-impedance amplifier which monitors the charge which moves through the "short circuit" to neutralise the stress-induced charge on the polymer. Alternatively, a high-impedance voltage amplifier can be used to measure the "open-circuit voltage",  $V$ , without removing significant charge.

Fig. 6 shows the arrangement of electrodes on a stretched poled film of PVDF. The polarisation and field which the electrodes register are, of course, the component in the "3" direction,  $P_3$  and  $E_3$ . Polarisation and tension ( $T$ ) in the "1" direction, are connected by a stress modulus,  $d$ , expressed in the form:

$$P_3 = d_{31}T_1. \quad (1)$$

Field and tension are connected by a related modulus,  $g$ .

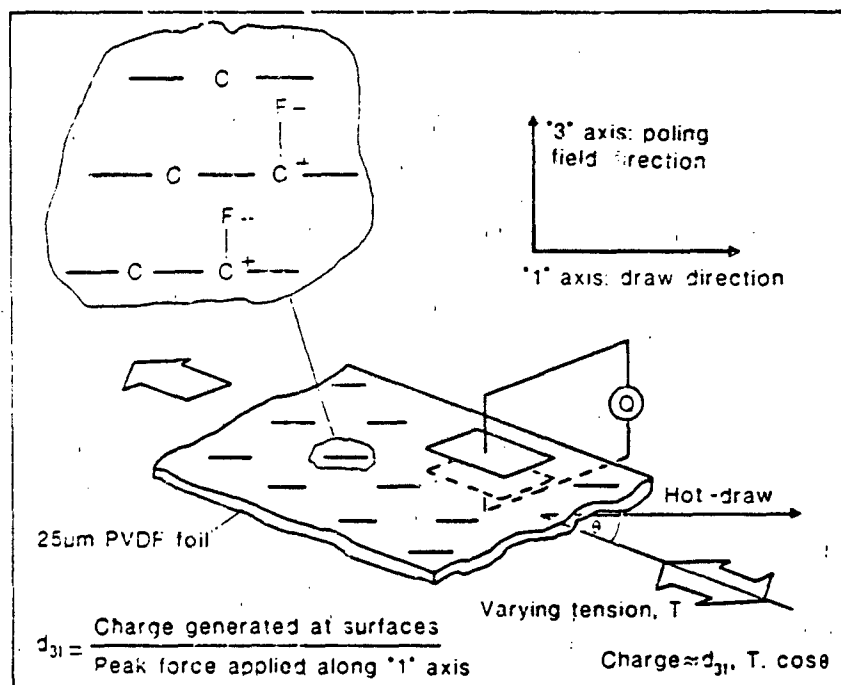
$$E_3 = g_{31}T_1. \quad (2)$$

Referring to Fig. 6, we can see that the  $d_{31}$  and  $d_{32}$  components determine the response to in-plane membrane forces, e.g. tension, while the  $d_{33}$  component determines the response to a force normal to the plane of the foil. In general,  $d_{31}$  and  $d_{32}$  are not equal. If stretching has occurred in the 1-direction only then  $d_{31} > d_{32}$ . PVDF sheet material which has been biaxially stretched during manufacture can also be made. For this material,  $d_{31}$  and  $d_{32}$  should be similar. Other components of the six-element matrix equation for piezoelectricity,  $d_{15}$  and  $d_{24}$ , determine the response to shear stresses. As a rule  $d_{33} > d_{31} > d_{32} > d_{15}, d_{24}$ . Table 2 gives a list of properties for films prepared by Yarsley while Table 3 gives a comparison of the properties of PVDF sensor material and other piezoelectric materials.

Table 4, gives a list of properties of the PVDF films prepared by the Penwalt Corporation.

The energy consumption of a PVDF device is basically small.<sup>22</sup> Consumption is composed of two components, steady-state and transient. The steady-state consumption arises from the finite resistivity of PVDF material of  $\sim 10^{15} \Omega\text{-cm}$ . Accordingly, if 100 volts dc is necessary to maintain a switched state, a PVDF bimorph using 9  $\mu\text{m}$ -thick film consumes  $2.2 \times 10^{-6}$  watts/cm<sup>2</sup>, a quite negligible value. Transient losses tend to be larger and depend on frequency, and whether or not pulse (digital) or sinusoidal conditions prevail. At the initial stage of digital switching (turn on), the capacitance between the electrodes is being charged. During this time an energy  $CV^2/2$  (joules) is consumed in the series resistance of the charging circuit, and an energy  $CV^2/2$  (joules) is stored in the device capacitance. To complete the switching cycle to the original unswitched condition, this stored energy is dumped into the resistor and, again,  $CV^2/2$  joules of energy is consumed. As a result,  $CV^2$  joules are consumed per complete switching cycle. Since the dielectric constant of PVDF is 12 and  $\epsilon$  is .400 pF/cm<sup>2</sup> for a bimorph using 9  $\mu\text{m}$ -thick film, then the power consumption is  $2.4 \times 10^{-5} \times n$  watts/cm<sup>2</sup> for  $n$  switching cycles per second for an excitation of 100 volts.

For the case of sinusoidal excitation, a capacitor does not consume  $CV^2$  energy, since the stored energy in each cycle is returned to the power source. Energy consumption is given by  $\omega CV^2 \tan \delta$ , where  $\delta$  is dielectric loss angle.



Simplified picture of the piezoelectric effect in poly(vinylidene fluoride). The film is hot-drawn to produce some parallelism of molecules and then warmed in a high electric field to produce some parallelism of the C-F dipoles. The highest piezoelectric signal for electrodes in the "3" direction is thus produced by a tension along the draw ("1") direction. For tensions in other directions, there are correspondingly reduced effects as shown.

FIGURE IV-6

TABLE IV-2

**Yarsley** Technical  
Centre

## Properties of Yarsley PVdF Films

Property	40 ± 3 μm		25 ± 2 μm		9 ± 1 μm		Units
Piezoelectric Coefficient*			d <sub>31</sub> 18-20 d <sub>32</sub> 2.8-3.2 g <sub>31</sub> 0.12-0.14 g <sub>32</sub> 0.013-0.022				pC/N pC/N Vm/N Vm/N
Pyroelectric Coefficient			24-28				μC/m <sup>2</sup> K
Surface Conductivity (metallised film A)			2				Ω <sup>-1</sup>
Tensile strength (at break)	MD 250-290	TD 34-36	MD 225-265	TD 34-36	MD 180-220	TD 29-35	× 10 <sup>6</sup> Nm <sup>-2</sup>
Elongation at break	MD 14-16	TD 430-450	MD 13-15	TD 440-490	MD 16-20	TD 300-400	%
Tensile Modulus	MD 2400-2700	TD 2300-2700	MD 2200-2600	TD 2000-2500	MD 1800-2200	TD 1750-2200	× 10 <sup>6</sup> Nm <sup>-2</sup>
Tear Strength (Machine Direction)	250-320		160-200		170-245		Nmm (thickness)
Dielectric constant (ε <sub>r</sub> )			12 ± 1				at 1 kHz
Dielectric loss tangent			0.02-0.025				at 1 kHz
Volume resistivity			5 × 10 <sup>12</sup>				Ω.m
Dielectric breakdown strength	135-145		160-170		290-310		kV(DC)/mm
Heat Shrinkage (machine direction after annealing at 70°C for 100 hours)	4.5		4.5		5.5		%

MD = Machine direction. TD = Transverse direction

\*d<sub>31</sub> > -d<sub>31</sub> and g<sub>31</sub> > -g<sub>31</sub>

The above property values are accurate to the best of our knowledge but are average figures

TABLE IV-2 (Continued)

**Yarsley** Technical  
Centre

### Ageing Characteristics

Thermal ageing tests on stability of piezoelectric coefficient and shrinkage in the machine direction have shown that Yarsley PVdF films are superior in ageing characteristics to all piezoelectric PVdF films previously commercially available.

### Stability of Coefficient (25 $\mu$ m Film)

Temperature (°C)	Time	$\frac{g_{\text{aged}}}{g_{\text{initial}}}$	$\frac{g_{\text{aged}}}{g_{\text{initial}}}$ Typical Commercial Film
90	100 minutes	0.91	0.71
120	100 minutes	0.71	0.45
150	100 minutes	0.35	0.20
67	2,500 hours	0.97	-
100	2,500 hours	0.77	-
-20--60--20	100 1 hr cycles	1.00	-

### Heat Shrinkage (25 $\mu$ m Film)

Temperature (°C)	Time	% Shrinkage (MD)	% Shrinkage (MD) Typical Commercial Film
90	100 minutes	- 3.5	- 3.8
120	100 minutes	- 8.1	-10.8
150	100 minutes	-19.2	-25.0
70	100 hours	- 4.5	- 5.0
65	2,500 hours	- 2.5	-
100	2,500 hours	-10.0	-

### Further Information and Technical Service

For further information and technical service on Yarsley PVdF films, please contact either:

Mr. M. H. Elson or  
Mr. A. P. Verrall

**Yarsley Research Laboratories Ltd.,**  
The Street, Ashted, Surrey, KT21 2AB.  
Telephone Ashted (03722) 76391/3.  
Telex 8951511. Cables 'Yarsleys Ashted'

For applications information and technical service on Yarsley PVdF films please contact:

Mr. P. D. Wilson

**Fulmer Research Laboratories Ltd.,**  
Stoke Poges, Slough SL2 4QD.  
Telephone Fulmer (02816) 2181. Telex 849374

All statements and technical information contained in this document are based on tests we believe to be reliable but the accuracy and completeness thereof is not guaranteed. We shall not be liable for any injury, loss of damage and/or death or property resulting from reliance on the information contained herein.

TABLE IV-3

MATERIAL	PIEZOELECTRIC CONSTANTS		PYROELECTRIC COEFFICIENT
	$d_{31}$ pC/N	$g_{31}$ Vm <sup>2</sup> /N	
PVDF	20	0.14	28
PZT-5	171	.011	60-500
BaTiO <sub>3</sub>	78	.005	200
QUARTZ	2	.05	—
TGS	—	—	350

Comparison of piezoelectric and pyroelectric properties of PVDF ceramics.

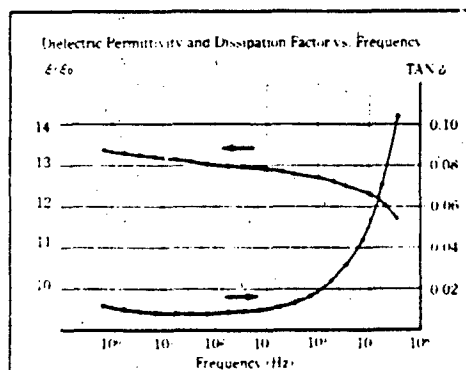


FIGURE IV-7

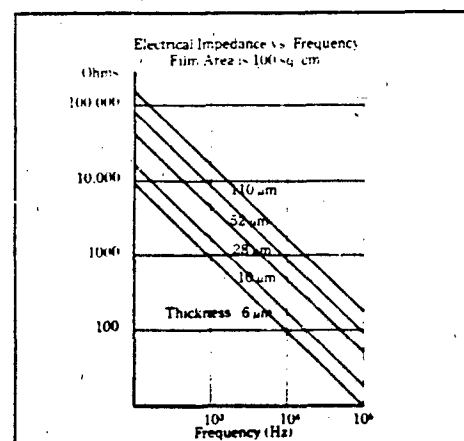


FIGURE IV-8

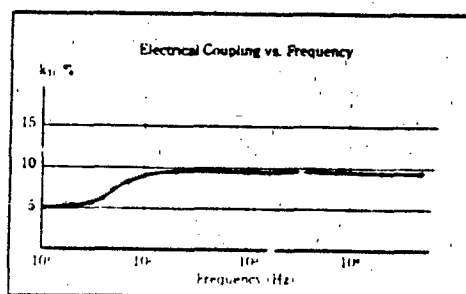


FIGURE IV-9

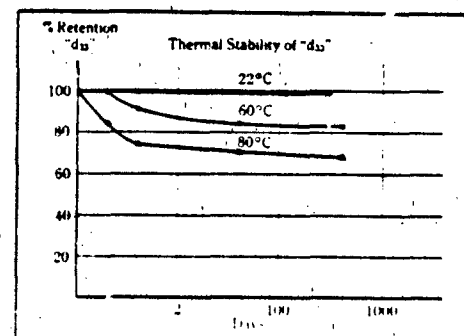


FIGURE IV-10

TABLE IV-4

## TYPICAL PROPERTIES OF KYNAR PIEZO FILM

PROPERTY		VALUE	UNITS
Thickness		6-125	$\mu\text{m}$
Surface Conductivity of Metallized Film	Al	1-4	$\Omega\text{cm}^{-1}$
	Ni	10-25	
Static Piezoelectric Strain Constant	$d_{31}$	20-25	$\text{pC}\cdot\text{N}^{-1}$ ( $\text{pm}\cdot\text{V}^{-1}$ )
	$d_{31}^*$	- 20-22	
Static Voltage Output Coefficient	$g_{31}$	0.230	$\text{Vm}\cdot\text{N}^{-1}$
	$g_{31}^*$	- 0.210	
Electromechanical Coupling Factor	$k_{31}$	9-15	% at 100 Hz
Piezoelectric Coefficient	$p$	- 23-27	$\mu\text{Cm}^{-2}\cdot\text{K}^{-1}$
Shrinkage in Machine Direction	60°C	2	% after annealing 100 hrs
	80°C	4	
Relative Dielectric Permittivity	$\epsilon/\epsilon_0$	12 ± 1	at 1000 Hz
Dielectric Loss Factor	$\tan \delta$	0.015-0.02	at 1000 Hz
Volume Resistivity	$\rho$	$10^{13}$	$\Omega\text{cm}$
Tensile Strength at Yield	MD**	-	$10^6\text{Nm}^{-2}$
	TD**	40-110	
Tensile Strength at Break	MD	160-330	$10^6\text{Nm}^{-2}$
	TD	30-55	
Elongation at Break	MD	25-40	%
	TD	380-430	
Young's Modulus of Elasticity = Elastic Stiffness = $c^E$	MD	1.5-3	$10^9\text{Nm}^{-2}$
	TD	1.1-2.4	
Melting Point		165-180	°C
Flammability, LOI		44	%O <sub>2</sub>
Thermal Conductivity		0.13	$\text{Wm}^{-1}\cdot\text{K}^{-1}$
Specific Heat		2.5	$\text{MJm}^{-3}\cdot\text{K}^{-1}$
Density		1.8	$\text{g}(\text{cm})^{-3}$
Thermal Expansion Coefficient		1.4	$10^{-4}\text{K}^{-1}$
Sound Velocity***		1.5-2.2	$\text{km}\cdot\text{s}^{-1}$

\*measurements were made in hydraulic press (see Fig. 1) \*\*MD = Machine Direction (1) and TD = Transverse Direction to film orientation (2)  
 \*\*\*longitudinal and thickness modes

The quantity  $\tan \delta$  has been measured in the frequency range 5-1000 Hz using a 150-volt signal. For display device purposes, in the low-frequency region,  $\tan \delta$  shows a constant value of 0.02 over the range 5-30 Hz for a single sheet PVDF layer. The energy consumption due to the dielectric loss is estimated to be  $4.8 \times 10^{-5}$  watts/cm<sup>2</sup> for 150 volts AC excitation at 7 Hz.

Additional properties of PVDF piezoelectric films are shown in Figs. 7 through 10. Fig. 7 illustrates the dependence of dielectric permittivity and dissipation factor on frequency at ambient temperature. As a result of its relatively low dielectric permittivity (100 fold less than piezo ceramics), the g-constants (voltage output coefficients) of PVDF are significantly greater than those of ceramics. Thus PVDF can be made into very responsive sensors of mechanical signals.

The relationships between electrical impedance and frequency for various thicknesses of KYNAR Piezo Film, 100 sq. cm in area, are shown in Fig. 8. These data are important for matching film impedance to associated components in the circuit. The influence of frequency on the electromechanical coupling factor " $k_{31}$ " is shown in Fig. 9. Although  $k_{31}$  and therefore the efficiency of energy transfer is low compared to ceramic transducers, KYNAR Piezo Film elements can be used at much higher fields than ceramics which result in desirable mechanical deflections. For example, because its dielectric strength is 70 times that of PZT ceramics, the maximum input capability for electrical energy of PVDF is 40 times greater and the corresponding output of mechanical energy is 5 times greater. Thermal stability data are presented in Fig. 10.

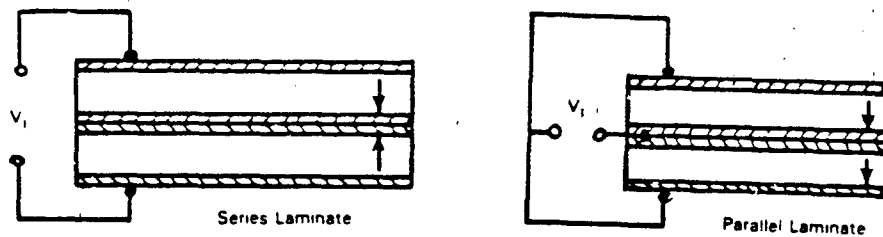
## 2. THEORETICAL ANALYSES

An extensive theoretical analysis of the characteristics of flexure mode devices was recently carried out by M.A. Marcus of the Eastman Kodak Company Research Laboratories.<sup>1</sup> Details of this analysis are presented below.

A piezoelectric flexure mode device has many layers of material with different piezoelectric activities. When an electric field is applied across the thickness of such a device, small differences in the amounts of expansion or contraction in the planes of the different layers are converted into large deflections of the layers out of their planes. Conversely, if an external force is applied to the device, causing it to flex, a voltage is generated across the thickness of the device. Polymeric piezoelectric flexure mode devices are receiving more attention in recent years because they offer a variety of advantages over ceramic piezoelectric transducers, including flexibility, ease of preparing large sheets, and the ability to undergo large deflections without damage. Many electromechanical applications of polymeric piezoelectric flexure mode devices have been reported. These include displays,<sup>1,2</sup> light deflectors,<sup>3-5</sup> optical scanners,<sup>4,5</sup> venetian blinds,<sup>6,7</sup> variable-aperture diaphragms,<sup>3</sup> vibrational fans,<sup>8</sup> shutters,<sup>3</sup> position sensors,<sup>9</sup> and deformable mirrors.<sup>10</sup>

Flexure mode devices can be constructed in a variety of configurations. The simplest configuration is the unimorph,<sup>5</sup> in which a single piezoelectric layer is bonded to a nonpiezoelectric substrate. The next device in complexity is the bimorph,<sup>11</sup> a sandwich of two piezoelectric sheets with a bonding layer between them. Two configurations of the bimorph are possible, depending on the external electrical connections (see Fig.11). In the series bimorph (Fig.11A) the external field is applied across the full thickness of the device, the polarization vectors of the piezoelectric sheets oppose each other, and no inner electrodes are required. In the parallel bimorph (Fig.11B) the external field is applied across each layer individually and a central conductor is necessary. In some cases it is desirable to increase the force capabilities of a flexure mode device. This can be done by a multilayer construction in which many piezoelectric layers are laminated.<sup>3,12</sup> This structure is called a multimorph, and care must be taken during construction so that all of the polarization vectors are properly aligned when the external field is applied across the device.

In previous analyses of piezoelectric polymer flexure mode devices it has been assumed that the piezoelectric activity distribution in the piezoelectric material is uniform throughout the thickness of the layer. Various workers<sup>13-17</sup> have shown that this may not be true in piezoelectric polymer flexure mode devices, because the piezoelectric activity distribution is a strong function of the poling conditions. In fact, it is possible to impart a high degree of asymmetry in activity throughout the thickness of a piezoelectric polymer film.<sup>17</sup> When this is done intentionally the device is called a monomorph.<sup>18</sup>



The two configurations of the piezoelectric bimorph

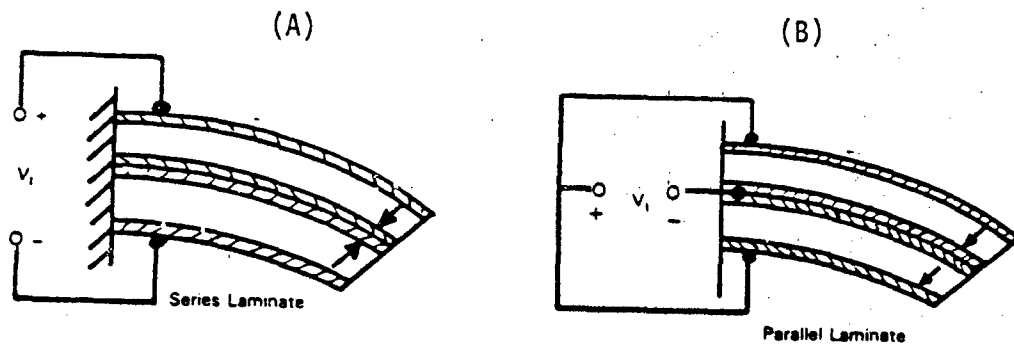
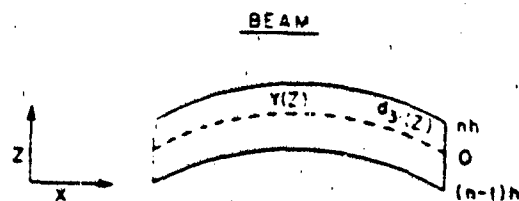
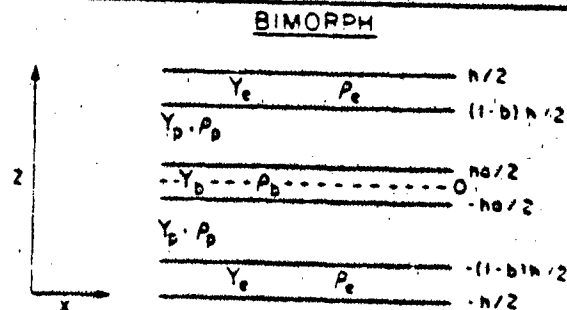


FIGURE IV-11



Geometry of a bent piezoelectric beam

FIGURE IV-12



Geometry and notation for a generalized bimorph beam with outer electrodes and bonding layers present

FIGURE IV-13

A design theory is presented for all of the above-mentioned flexure mode devices. The effects of electrodes and bonding layers are included in the analysis. The performance of a polymeric piezoelectric flexure mode device is strongly dependent upon bonding-layer properties and electrode choice and thickness.

Application of an electric field across the thickness of a piezoelectric material produces mechanical stresses. If the piezoelectric activity of the piezoelectric material is distributed inhomogeneously throughout the thickness of the beam, bending will occur. Bending can also be caused to occur by applying the electric field so that the mechanical stress is tensile near one surface and compressive at the other.

Fig.12 shows the general structure of a bent piezoelectric beam. The  $z$  direction is the thickness dimension, and the total thickness of the beam is  $h$ . Bending occurs with respect to the neutral axis (origin), and  $n$  is a number between 0 and 1 that indicates the percentage of the beam located above the neutral axis. For a symmetrical beam  $n=0.50$ . The neutral axis is located by setting the moment of the area of a cross section of the beam with respect to the neutral axis equal to zero.<sup>19</sup> For a beam within its elastic limit, it can be shown that the strain  $S_1(z)$  is related to the radius of curvature ( $R$ ) of the section by

$$S_1 = z/R. \quad (1)$$

For beams with large ratios of length to thickness, the radius of curvature is constant and the neutral axis can be found from

$$1/R \int_{(n-1)h}^{nh} Y(z)zdz = 0 \quad (2)$$

where  $Y(z)$  is Young's modulus as a function of thickness. For any beam the externally imposed bending moment must equal the internal resisting moment. For free deflection of a piezoelectric cantilever beam, the external moment is zero. Thus

$$\int_{(n-1)h}^{nh} zT_1 dA = 0 \quad (3)$$

where  $T_1$  is the stress and  $dA = w dz$  is the elemental area with beam width  $w$ . In a piezoelectric material the stress  $T_1$  is related to the strain  $S_1$  by the relationship

$$S_1 = s_{11}T_1 + d_{31}E_3 \quad (4)$$

when  $T_2 = T_3 = T_4 = T_5 = T_6 = 0$ . Here  $s_{11}$  is an elastic compliance tensor element which is related to Young's modulus by

$$Y(z) = 1/s_{11}, \quad (5)$$

$d_{31}$  is a piezoelectric strain tensor component, and  $E_3$  is the applied electric field. Substitution of Eqs. (1), (4), and (5) into Eq. (3) yields

$$1/R = \frac{\int_{(n-1)h}^{nh} Y(z) d_{31}(z) E_3 z \, dz}{\int_{(n-1)h}^{nh} Y(z) z \, dz}. \quad (6)$$

For a beam of length  $L$  the displacement at the end of the cantilever  $\delta$  is

$$\delta = R(1 - \cos L/R). \quad (7)$$

When the radius of curvature is large with respect to the beam length,

$$\delta \approx L^2/2R. \quad (8)$$

The radius of curvature and hence the deflection of the tip of the cantilever depend upon the distribution of Young's modulus, the piezoelectric activity, and the applied electric field across the piezoelectric layers. The effects of varying these quantities will be described below.

To calculate the natural vibrational frequencies for a composite beam, we need to solve the partial differential equation for transverse vibrations in a beam with the appropriate boundary conditions for cantilever mounting. The transverse wave equation to be solved is<sup>20</sup>

$$\frac{\partial^2 z}{\partial t^2} = - \frac{(YI)}{m} \frac{\partial^4 z}{\partial x^4} \quad (9)$$

where  $(YI)$  is the modulus, moment of inertia product and  $m$  is the mass per unit length of the beam. For cantilever beam mounting the boundary conditions are

$$z = 0 \quad \text{and} \quad \frac{\partial z}{\partial x} = 0 \quad (10)$$

at  $x = 0$  and

$$\frac{\partial^2 z}{\partial x^2} = 0 \text{ and } \frac{\partial^3 z}{\partial x^3} = 0 \quad (11)$$

at  $x = L$ . The resonance frequencies for this structure are given by

$$f_i = \frac{\pi}{8L^2} \sqrt{\frac{YI}{m}} (1.194^2, 2.988^2, 5^2, 7^2 \dots). \quad (12)$$

Another quantity of interest in the cantilever beam system is the deflection bandwidth product (DBWP).<sup>5</sup> It is given by the product of the DC deflection and the fundamental resonance frequency of the device. It is independent of the device dimensions and depends only on materials parameters and the applied electric field. It is a useful figure of merit for devices in which both large motion and high speed are desirable. Examples of such devices are switches, laser scanners, and displays.

Fig.13 shows the structure of a piezoelectric bimorph structure with the outer electrodes included. Because this is a symmetric structure, the neutral axis is located in the geometric center of the device. The total device thickness is  $h$ , each electrode has a thickness of  $bh/2$ , and there is a central bonding layer of thickness  $ha$ . Solving Eq. (6) for the radius of curvature yields

$$\frac{I}{R} = \frac{3d_{31}E_3}{h} \frac{Y_p[(1-b)^2 - a^2]}{Y_b a^3 + Y_p[(1-b)^3 - a^3] + Y_e[1 - (1-b)^3]} \quad (13)$$

where  $Y_p$ ,  $Y_b$ , and  $Y_e$  are Young's moduli for the piezoelectric, bonding, and electrode layers, respectively. To calculate the resonance frequency of this device we need to know the mass per unit length. The mass per unit length per unit width is given by

$$m = \rho_b ha + \rho_e hb + \rho_p h(1 - a - b) \quad (14)$$

where  $\rho_b$ ,  $\rho_p$ , and  $\rho_e$  are the density of the bonding, piezoelectric, and electrode layers, respectively. The fundamental resonance frequency is given by

$$f_1 = 0.162 \frac{h}{L^2} \left( \frac{Y_b a^3 + Y_p[(1-b)^3 - a^3] + Y_e[1 - (1-b)^3]}{\rho_b a + \rho_e b + \rho_p(1 - a - b)} \right)^{1/2} \quad (15)$$

For small angles the deflection bandwidth product is given by

$$\text{DBWP} = 0.243 d_{31} E_3 \frac{Y_p [(1-b)^2 - a^2]}{(Y_b a^3 + Y_p [(1-b)^3 - a^3] + Y_e [1 - (1-b)^3])^{1/2}} \quad (16)$$

$$\times [\rho_b a + \rho_e b + \rho_p (1-a-b)]^{1/2}$$

When  $a = 0$  and  $b = 0$ , the expressions for deflection, resonance, frequency, and DBWP reduce to

$$\delta = \frac{3 d_{31} E_3 L^2}{2h} \quad (17)$$

$$f = 0.162 (Y_p / \rho_p)^{1/2} h / L^2 \quad (18)$$

$$\text{DBWP} = 0.243 (Y_p / \rho_p)^{1/2} d_{31} E_3 \quad (19)$$

which are the correct expressions for the ideal piezoelectric bimorph. The case for which  $b = 0$  has been discussed in detail in Ref. 5. There it was shown that the DBWP of a polymer piezoelectric cantilever beam could be improved by adding a low-density, low-modulus, central bonding layer of finite thickness to the beam. Tables 5-7 demonstrate the effects of aluminum electrodes 0, 500, and 1000 Å thick on the flexure and resonance behavior of cantilever beams. As the thickness of the piezoelectric layers is decreased, the electrode effects become even more pronounced. For a 1-cm-long beam constructed of 9-μm-thick poly(vinylidene fluoride) (PVDF) operating at 100 V, the deflection is lowered from 1.85 to 1.33 mm for 500-Å-thick electrodes and no bonding layer.

TABLE IV-5

Piezoelectric bimorph deflection bandwidth

Piezoelectric layer thickness =  $9 \times 10^{-6}$  m  
 $Y_p = 3 \times 10^{10}$  N/m<sup>2</sup>  
 $Y_b = 1.1 \times 10^{10}$  N/m<sup>2</sup>  
 Electrode thickness = 0 m  
 $Y_e = 7 \times 10^{10}$  N/m<sup>2</sup>  
 $d_{31} = 2 \times 10^{-11}$  m/V  
 Applied voltage = 100 V  
 Length of beam = 0.01 m  
 Density of the piezoelectric layer = 1780 kg/m<sup>3</sup>  
 Density of the bonding layer = 890 kg/m<sup>3</sup>  
 Density of the electrode = 2700 kg/m<sup>3</sup>

Bonding Layer Thickness ( $\mu$ m)	Beam Tip Deflection (mm)	Resonance Freq (Hz)	DBWP (cm-Hz)	Total Thickness ( $\mu$ m)
0.00	1.85	37.76	6.99	18.0
0.5	1.80	39.08	7.04	18.5
1.00	1.75	40.39	7.07	19.0
1.50	1.70	41.71	7.09	19.5
2.00	1.65	43.03	7.11	20.0
2.50	1.60	44.34	7.12	20.5
3.00	1.56	45.65	7.12	21.0
3.50	1.52	46.96	7.12	21.5
4.00	1.47	48.26	7.11	22.0
4.50	1.43	49.56	7.11	22.5
5.00	1.40	50.85	7.09	23.0
5.50	1.36	52.13	7.08	23.5
6.00	1.32	53.40	7.06	24.0
6.50	1.29	54.67	7.05	24.5
7.00	1.26	55.93	7.03	25.0
7.50	1.23	57.18	7.01	25.5
8.00	1.20	58.43	6.99	26.0
8.50	1.17	59.66	6.96	26.5
9.00	1.14	60.89	6.94	27.0
9.50	1.11	62.11	6.92	27.5
10.0	1.09	63.32	6.89	28.0
10.5	1.06	64.52	6.87	28.5
11.0	1.04	65.72	6.84	29.0
11.5	1.02	66.90	6.81	29.5
12.0	0.997	68.08	6.79	30.0
12.5	0.977	69.25	6.76	30.5
13.0	0.957	70.41	6.74	31.0
13.5	0.938	71.56	6.71	31.5
14.0	0.919	72.70	6.68	32.0
14.5	0.902	73.84	6.66	32.5
15.0	0.884	74.97	6.63	33.0
15.5	0.868	76.09	6.60	33.5
16.0	0.852	77.20	6.58	34.0
16.5	0.837	78.31	6.55	34.5
17.0	0.822	79.40	6.53	35.0
17.5	0.806	80.49	6.50	35.5
18.0	0.794	81.58	6.47	36.0
18.5	0.780	82.65	6.45	36.5
19.0	0.767	83.72	6.42	37.0
19.5	0.755	84.78	6.40	37.5
20.0	0.742	85.84	6.37	38.0

# PERFORMANCE OF FLEXURE MODE DEVICES

## TABLE IV-6

Piezoelectric bimorph deflection bandwidth

Piezoelectric layer thickness =  $9 \times 10^{-6}$  m

$\gamma_p = 3 \times 10^8$  N/m<sup>2</sup>

$\gamma_b = 1.1 \times 10^8$  N/m<sup>2</sup>

Electrode thickness =  $5 \times 10^{-6}$  m

$\gamma_e = 7 \times 10^{10}$  N/m<sup>2</sup>

$d_{31} = 2 \times 10^{-11}$  m/V

Applied voltage = 100 V

Length of beam = 0.01 m

Density of the piezoelectric layer = 1780 kg/m<sup>3</sup>

Density of the bonding layer = 890 kg/m<sup>3</sup>

Density of the electrode = 2700 kg/m<sup>3</sup>

Bonding Layer Thickness ( $\mu$ m)	Beam Tip Deflection (mm)	Resonance Freq (Hz)	DBWP (cm-Hz)	Total Thickness ( $\mu$ m)
0.00	1.33	44.35	5.90	18.1
0.50	1.30	45.72	5.96	18.6
1.00	1.28	47.09	6.01	19.1
1.50	1.25	48.46	6.05	19.6
2.00	1.22	49.83	6.09	20.1
2.50	1.19	51.20	6.11	20.6
3.00	1.17	52.56	6.14	21.1
3.50	1.14	53.92	6.15	21.6
4.00	1.12	55.27	6.16	22.1
4.50	1.09	56.62	6.17	22.6
5.00	1.07	57.96	6.18	23.1
5.50	1.04	59.29	6.18	23.6
6.00	1.02	60.61	6.18	24.1
6.50	0.997	61.93	6.18	24.6
7.00	0.976	63.24	6.17	25.1
7.50	0.955	64.54	6.16	25.6
8.00	0.935	65.83	6.16	26.1
8.50	0.916	67.12	6.15	26.6
9.00	0.897	68.40	6.14	27.1
9.50	0.879	69.66	6.12	27.6
10.0	0.862	70.92	6.11	28.1
10.5	0.845	72.17	6.10	28.6
11.0	0.829	73.42	6.08	29.1
11.5	0.813	74.65	6.07	29.6
12.0	0.798	75.88	6.05	30.1
12.5	0.783	77.09	6.04	30.6
13.0	0.769	78.30	6.02	31.1
13.5	0.755	79.50	6.00	31.6
14.0	0.742	80.70	5.99	32.1
14.5	0.729	81.88	5.97	32.6
15.0	0.716	82.06	5.95	33.1
15.5	0.704	84.23	5.93	33.6
16.0	0.692	85.39	5.91	34.1
16.5	0.681	86.54	5.89	34.6
17.0	0.670	87.69	5.88	35.1
17.5	0.659	88.83	5.86	35.6
18.0	0.649	89.96	5.84	36.1
18.5	0.639	91.08	5.82	36.6
19.0	0.629	92.20	5.80	37.1
19.5	0.620	93.30	5.78	37.6
20.0	0.610	94.41	5.76	38.1

TABLE IV-7

Piezoelectric bimorph deflection bandwidth

Piezoelectric layer thickness =  $9 \times 10^{-6}$  m $Y_p = 3 \times 10^{10}$  N/m<sup>2</sup> $Y_e = 1.1 \times 10^{10}$  N/m<sup>2</sup>Electrode thickness =  $1 \times 10^{-6}$  m $Y_e = 7 \times 10^{10}$  N/m<sup>2</sup> $d_{31} = 2 \times 10^{-11}$  m/V

Applied voltage = 100 V

Length of beam = 0.01 m

Density of the piezoelectric layer = 1780 kg/m<sup>3</sup>Density of the bonding layer = 890 kg/m<sup>3</sup>Density of the electrode = 2700 kg/m<sup>3</sup>

Bonding Layer Thickness ( $\mu$ m)	Beam Tip Deflection (mm)	Resonance Freq (Hz)	DBWP (cm-Hz)	Total Thickness ( $\mu$ m)
0.00	1.04	50.05	5.19	18.2
0.50	1.02	51.49	5.25	18.7
1.00	1.00	52.92	5.31	19.2
1.50	0.985	54.35	5.35	19.7
2.00	0.967	55.78	5.40	20.2
2.50	0.949	57.21	5.43	20.7
3.00	0.931	58.63	5.46	21.2
3.50	0.913	60.05	5.48	21.7
4.00	0.895	61.45	5.50	22.2
4.50	0.878	62.86	5.52	22.7
5.00	0.861	64.25	5.53	23.2
5.50	0.844	65.64	5.54	23.7
6.00	0.828	67.02	5.55	24.2
6.50	0.812	68.39	5.55	24.7
7.00	0.797	69.75	5.56	25.2
7.50	0.782	71.11	5.56	25.7
8.00	0.767	72.45	5.56	26.2
8.50	0.753	73.79	5.55	26.7
9.00	0.739	75.12	5.55	27.2
9.50	0.726	76.44	5.54	27.7
10.0	0.712	77.75	5.54	28.2
10.5	0.700	79.05	5.53	28.7
11.0	0.687	80.35	5.52	29.2
11.5	0.676	81.63	5.51	29.7
12.0	0.664	82.91	5.50	30.2
12.5	0.653	84.18	5.49	30.7
13.0	0.642	85.44	5.48	31.2
13.5	0.631	86.69	5.47	31.7
14.0	0.621	87.93	5.46	32.2
14.5	0.611	89.16	5.45	32.7
15.0	0.601	90.39	5.43	33.2
15.5	0.594	91.61	5.42	33.6
16.0	0.582	92.83	5.41	34.1
16.5	0.571	94.05	5.40	34.6
17.0	0.560	95.27	5.38	35.1
17.5	0.549	96.49	5.36	35.6
18.0	0.549	97.71	5.34	36.1
18.5	0.539	98.93	5.32	36.6
19.0	0.533	100.15	5.30	37.2
19.5	0.525	101.37	5.31	37.7
20.0	0.518	102.59	5.29	38.2

### 3. EXPERIMENTAL INVESTIGATIONS

#### a. Fabrication of Piezoelectric Bimorph Elements

The PVDF bimorphs were fabricated from commercially polarized uniaxially oriented films supplied by the Pennwalt and Yarsley Corporations. The thinnest films currently available, 6, 9, 16 and 25 microns, were utilized. The film constants are indicated in Tables 2 and 4. The bonding adhesive utilized was duro E-Pox-E5 resin and hardner. For simplicity, leads were constructed of smooth copper foil backed by conducting adhesive manufactured by the 3M Company. Electrodes were aluminum and aluminum-nickel.

The two basic bimorph configurations shown in Figs. 11A and 11B were utilized.

It was found that bimorph elements could easily be fabricated utilizing razors or scissors to cut the films to the desired dimensions. No tendency to short across the thin layer was observed in the fabrication of the bimorph elements when the electrodes were attached. It was observed, however, that unless the electrodes were carefully attached to the metalized surfaces with conducting adhesive, in some cases the deposited electrode could be removed.

The use of the 3M conducting adhesive to form the leads attached to the electrode material was initially selected only to provide a limited life connection electrode for examination of the bimorph performance. Test indicated, however, that over a period of several months, consistent bimorph performance could be measured suggesting that no deterioration of the bond or removal of the metalization by the adhesive had occurred. The conducting adhesive was found to provide an adequate bond if the metallization was not removed from the film.

#### b. Bimorph Test Results

Results of typical static bimorph tests are shown in Figs. 14 to 21. Two-electrode bimorph results are shown in Figs. 14 to 17. The tip deflection can be observed to vary directly with the square of the length parameter and inversely with the thickness as indicated by the theory, Eq. 17. The observed tip deflections are, in general, for a given geometry, smaller than the corresponding deflections observed for the three-electrode configurations, Figs. 14-21, Tables 8 to 10.

This difference was attributed primarily to the somewhat lower field strength for the simpler two-electrode configuration. In addition, since more two-electrode bimorph configurations were constructed and tested, some influence of the lack of uniformity of poling conditions might have resulted when large batches of piezoelectric films were prepared. The Pennwalt corporation has recently indicated that it is improving its quality control procedures, Exhibit A.

All dc static deflection tests were conducted with simple batteries since current requirements and energy consumption were minimal as indicated in the

theoretical discussion.

Dynamic tests were conducted with pulse generations obtained from the TRI-PHENIX Corporation.

The frequency characteristic of the displacement for an ideal one-end clamped structure is approximately flat from dc out to the region of mechanical resonance. Since ideal bimorph performance is not always observed for the bimorphs constructed with a finite adhesive layer, it has been suggested that the deflection at resonance is substantially greater than that observed in dc operation. The theoretical analysis by Marcus; confirmed by the experimental results of Toda<sup>2</sup>, Figs. 22-23, indicates that in the dc displacement amplitude should equal that observed at resonance.

An apparent "increase" in tip displacement at resonance for bimorphs in dynamic ac and dc tests was also indicated in the current tests, Figs. 24-30. However, when compared to the theoretical results, Table 5, the deflection at resonance was smaller than the theoretical value, although substantially larger than the indicated static displacement. This suggests that even though the stretched and poled film may not possess the theoretical characteristics as a result of poling operation at, or near, the natural frequency, can yield the maximum displacement for a given voltage if this maximum value is not also obtained in the dc static displacement configuration.

An interesting difference was observed between the performance of the two- and three-electrode configurations. When excited, by a single pulse, the decay time for the two configurations showed remarkably different results. The two-electrode bimorph configuration acted in a manner similar to that of a slowly discharging capacitor, decay times of over 6 seconds being observed before reaching values of  $1/e$  of the original amplitude. The 3-electrode bimorph configuration discharged much more rapidly, values of  $1/e$  being achieved in approximately  $1\frac{1}{2}$  seconds. This behavior suggests that the bimorph elements can function as if they possess a memory capability.

Tests of performance over periods of time to assess performance change were also undertaken. When leads to the electrodes were carefully attached and the metallization adhered firmly to the film, no change in performance, static or dynamic, was observed in test periods of over two months of intermittent operation. The tests suggested that reliable and long operational life could be achieved with optical valves based on the mechanical modulation of light beams utilizing these relatively new PVDF piezoelectric films.

The test results further suggested that a wide range of valve operation could be achieved with different bimorph configurations. Optical valves based on the use of these films can be constructed for "static" or slowly varying informational displays as well as dynamic displays requiring rapid value motions of 60 Hz or greater frequencies. The analysis of Marcus, Tables 5 to 7, suggests that frequencies greater than 60 Hz can be achieved. In the current tests, Fig. 26, frequencies of approximately 40 Hz were utilized. For both static and dynamic operational modes, the amplitude of the displacement is controlled directly by the applied voltage.

Stages in the fabrication and testing of the piezoelectric film bimorphs are shown in Figs. 31 to 39.

Two Electrode Configuration

Dimensions

Length - 30mm

Width - 7mm

Thickness - 40 $\mu$ m

Negative outside Polarity

Voltage	Average Deflection (mm)
27 Volts	0.2
36 Volts	0.5
45 Volts	1.0
54 Volts	1.8

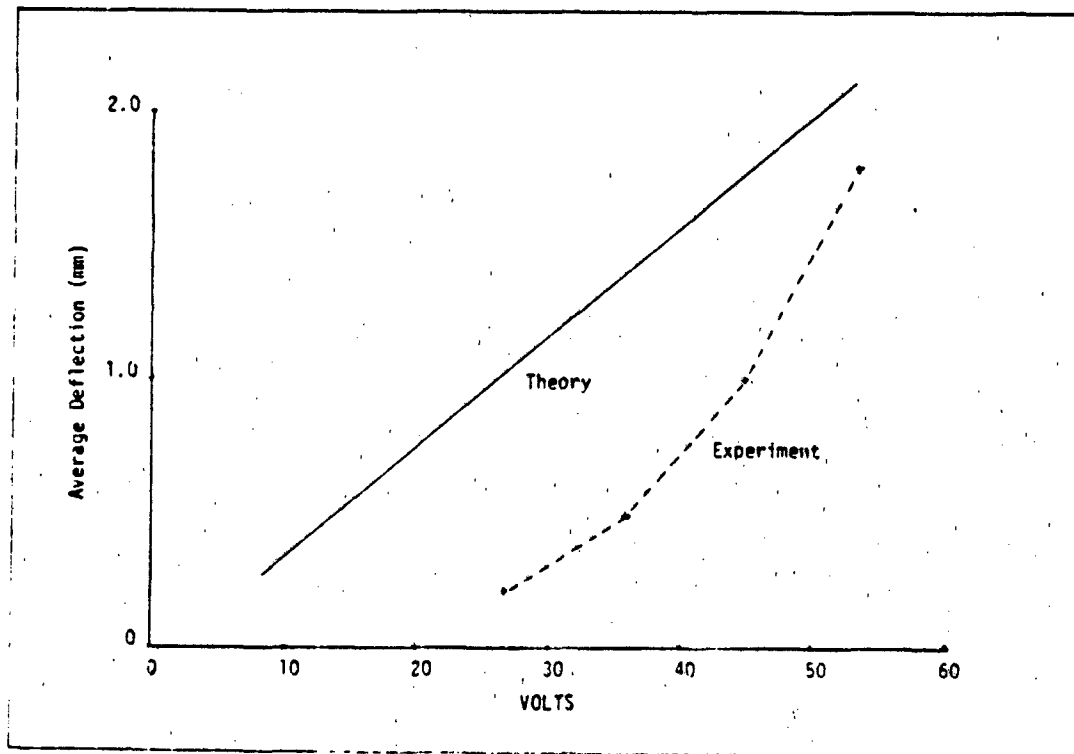


FIGURE IV-14

Two Electrode Configuration

Dimensions

Length - 32mm

Width - 7.5mm

Thickness - 20 $\mu$ m

Positive outside Polarity

Voltage	Average Deflection (mm)
18 Volts	0.7
27 Volts	1.1
36 Volts	2.3
45 Volts	4.0
54 Volts	6.3

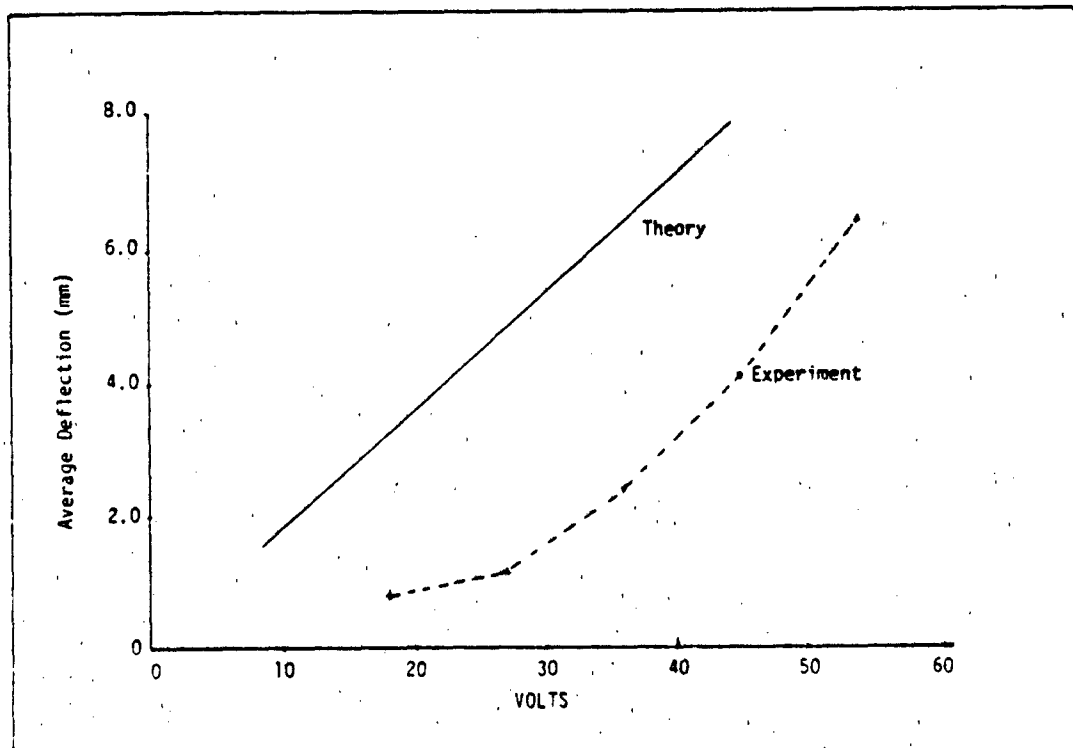


FIGURE IV-15

Two Electrode Configuration

Dimensions

Length - 32mm

Width - 7mm

Thickness 35 $\mu$ m

Negative outside Polarity

Voltage	Average Deflection (mm)
18 Volts	0.2
27 volts	0.9
36 Volts	1.3
45 Volts	1.9
54 Volts	2.5

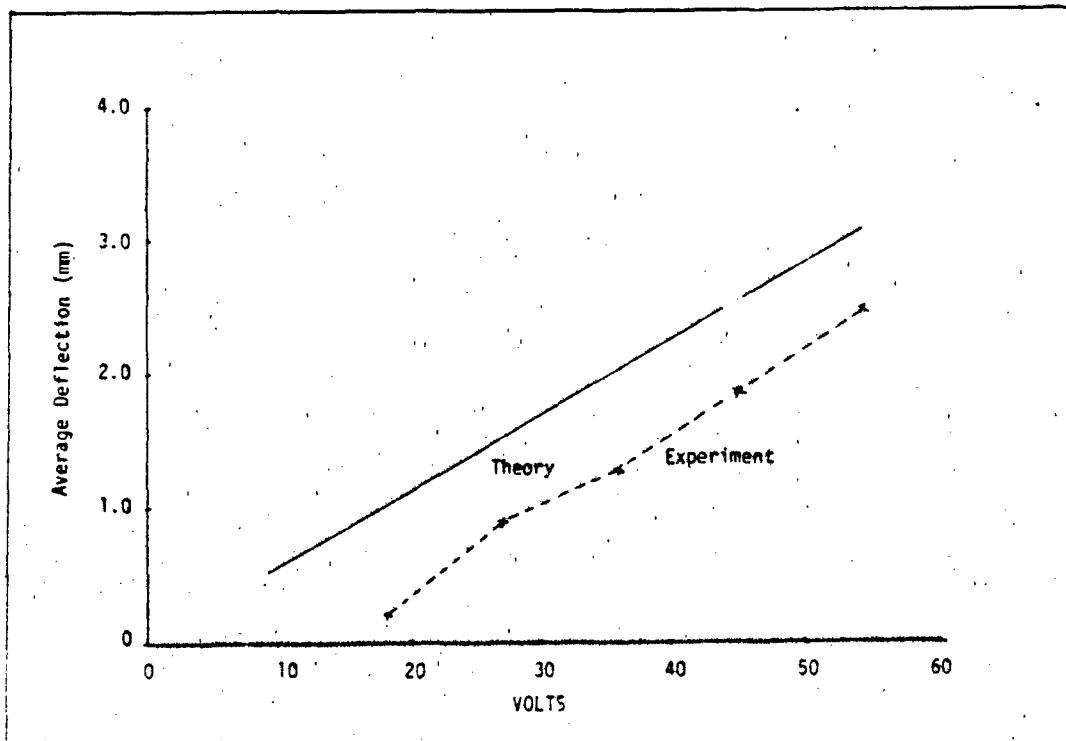


FIGURE IV-16

Two Electrode Configuration

Dimensions

Length - 32mm

Width - 7mm

Thickness 40 $\mu$ m

Negative outside Polarity

Voltage	Average Deflection (mm)
18 Volts	0.1
27 Volts	0.2
36 Volts	0.5
45 Volts	1.5
54 Volts	2.2

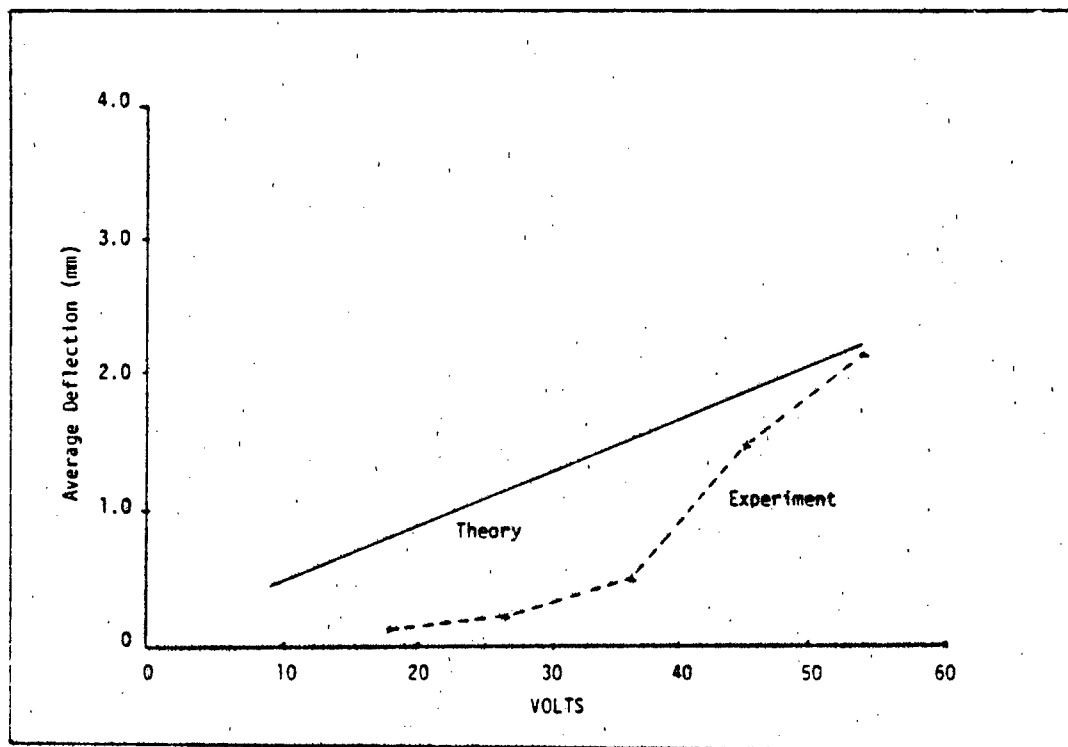


FIGURE IV-17

Three Electrode Configuration

Dimensions

Length - 30mm

Width - 8mm

Thickness - 25 $\mu$ m

Positive outside Polarity

Voltage	Average Deflection (mm)
18 Volts	1.3
27 Volts	2.0
36 Volts	3.0
45 Volts	4.0
54 Volts	5.0

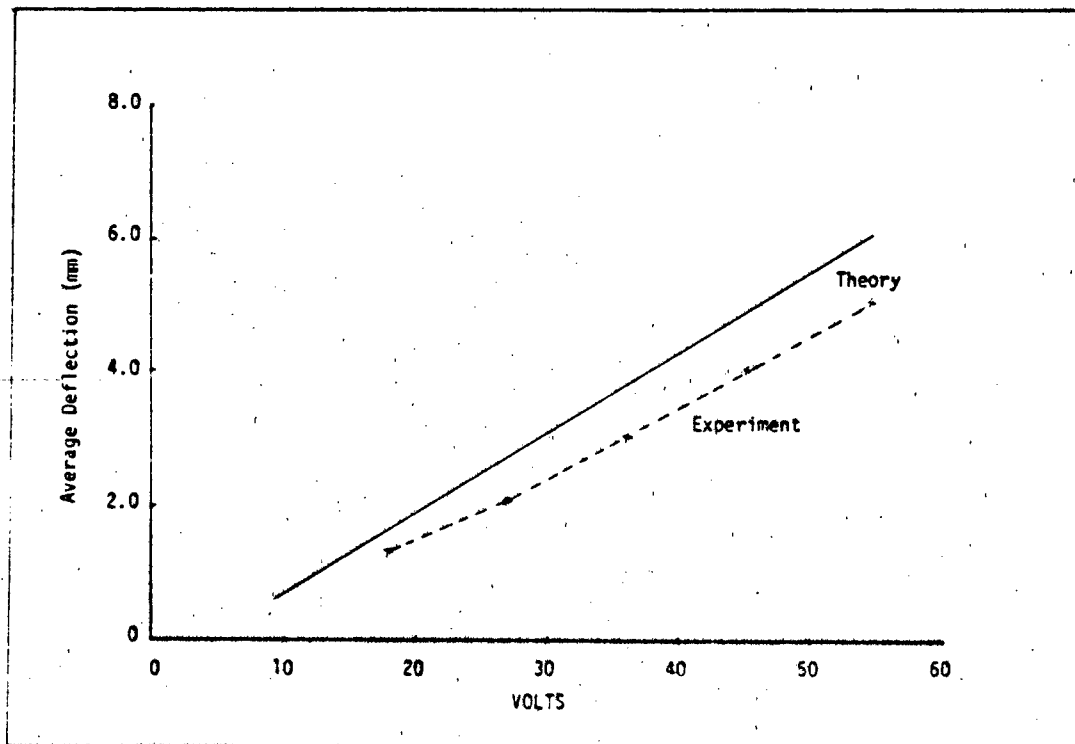


FIGURE IV-18

Three Electrode Configuration

Dimensions

Length - 30mm

Width - 7.5mm

Thickness - 28 $\mu$ m

Negative outside Polarity

Voltage	Average Deflection (mm)
18 Volts	2.0
27 Volts	2.5
36 Volts	3.0
45 Volts	3.5
54 Volts	4.2

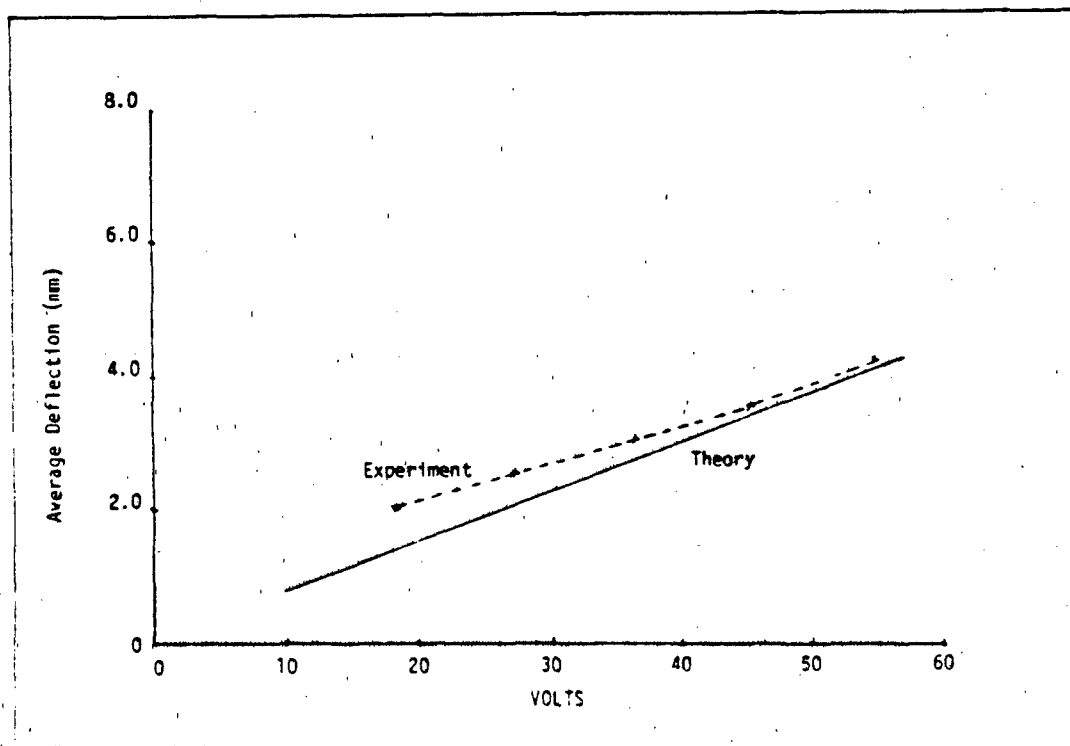


FIGURE IV-19

Three Electrode Configuration

Dimensions

Length - 31mm

Width - 7mm

Thickness - 30 $\mu$ m

Negative outside Polarity

Voltage	Average Deflection (mm)
18 Volts	1.5
27 Volts	2.0
36 Volts	3.0
45 Volts	3.5
54 Volts	4.0

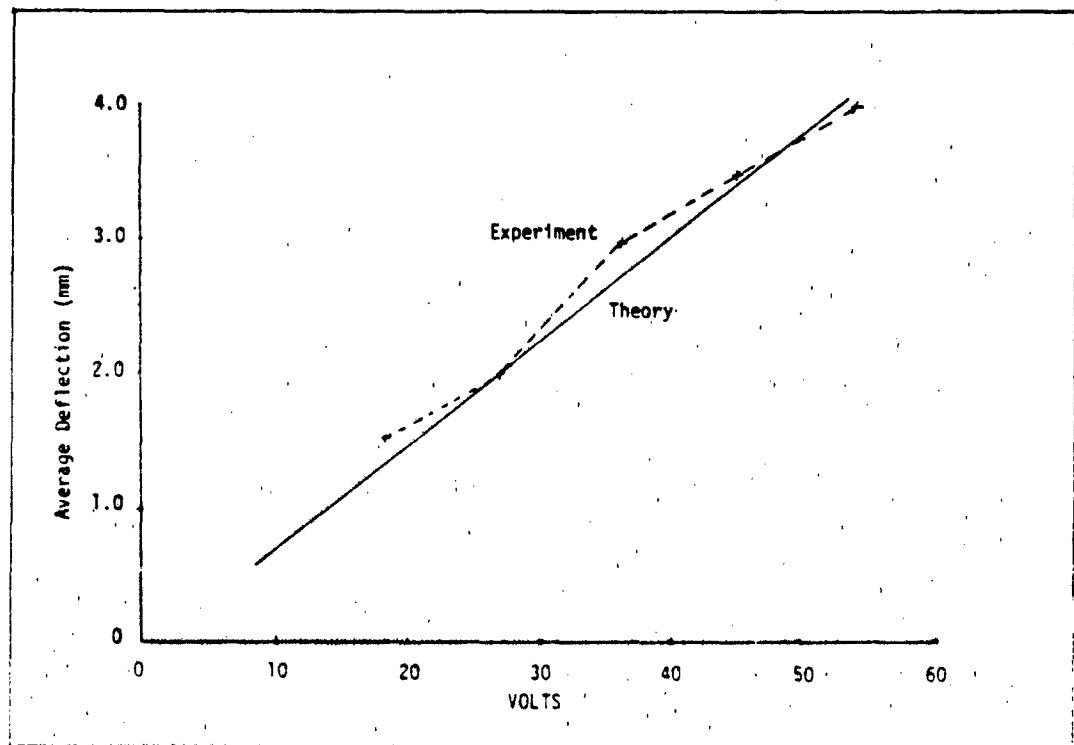


FIGURE IV-20

Three Electrode Configuration

Dimensions

Length - 31mm

Width - 7mm

Thickness - 30 $\mu$ m

Positive outside Polarity

Voltage	Average Deflection (mm)
18 Volts	1.0
27 Volts	2.0
36 Volts	2.8
45 Volts	3.5
54 Volts	4.0

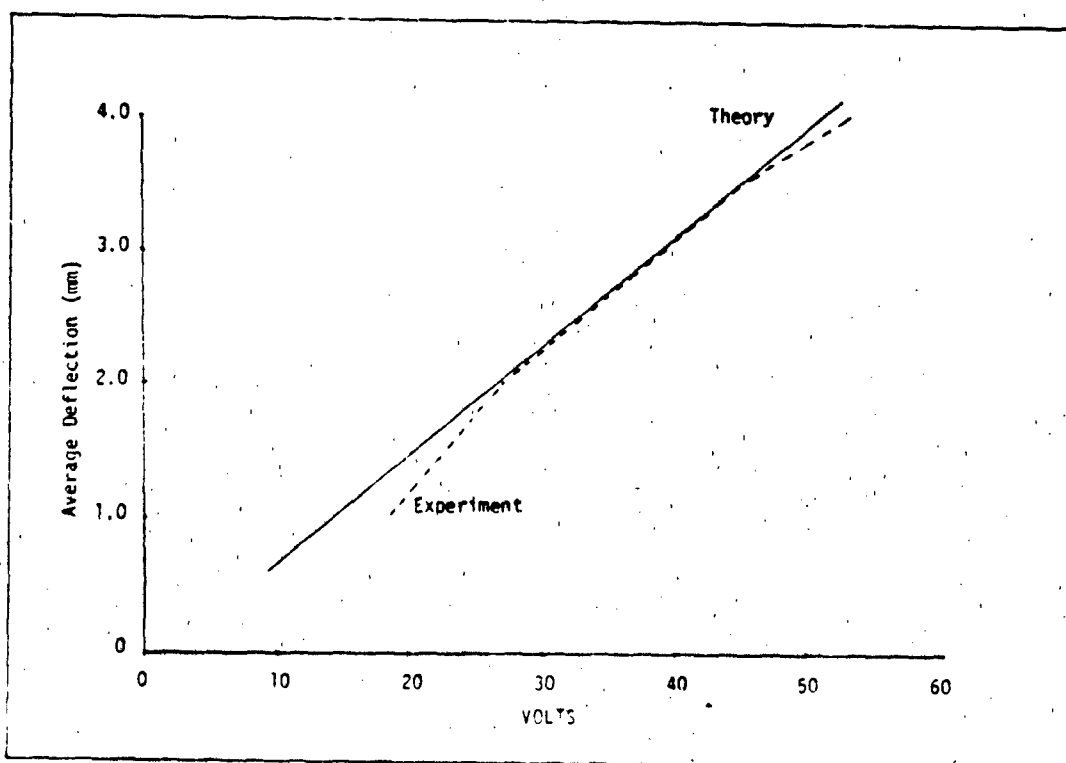


FIGURE IV-21

TABLE IV-8

2-ELECTRODE BIMORPH TESTS						
Dimensions of Bimorph			Upper Surface	Deflection (mm)	at 54 V.	
Length (mm)	Thickness ( $\mu$ m)	Width (mm)	Polarity +, -	54 V.	Theoretical	% of Theory
23	18	6	+	1.9	6.08	31.3
20	21	8	-	0.7	3.38	20.7
23	25	7	-	0.5	3.15	15.9
26	25	7	-	0.7	4.03	17.4
28	25	7	-	0.2	4.67	4.3
30	25	7	-	1.0	5.37	18.6
30	28	7	-	0.9	4.28	21.0
26	30	7	-	0.9	2.80	32.1
25	31	7	-	1.0	2.42	41.3
20	35	7	-	1.0	2.38	42.0
30	35	8	+	1.0	2.73	36.6
25	38	7.5	-	0.8	1.61	49.7
29	38	7	-	0.9	2.17	41.5
28	39	7	-	1.2	1.92	62.5
25	40	7	-	0.5	1.46	34.2
27	40	7	-	1.0	1.70	58.8
30	40	8	-	1.8	2.09	86.1
31	40	6	-	0.3	2.24	13.4
32	40	7	-	2.0	2.38	84.0
23	45	7	-	0.5	0.97	51.5

TABLE IV-9

2 ELECTRODE BIMORPH TESTS										
Dimensions of Bimorph			Upper Surface	Deflection (mm)					at 54 V.	
Length (mm)	Thickness ( $\mu$ m)	Width (mm)	Polarity +, -	54 V.	45 V.	36 V.	27 V.	18 V.	Theoretical	% of Theory
35	25	7	-	3.0	2.1	1.2	0.6		7.30	41.1
32	20	7.5	+	6.3	4.0	2.3	1.1	0.7	9.53	66.1
30	40	7	-	1.8	1.0	0.5	0.2		2.09	86.1
32	35	7	-	2.5	1.9	1.3	0.9	0.2	3.11	80.4
32	40	7	-	2.2	1.5	0.5	0.2	0.1	2.38	92.4

TABLE IV-10

## 3 - ELECTRODE BIMORPH TESTS

Dimensions of bimorph			Center electrode	Deflection (mm)					at 54 V.	% of Theory
Length (mm)	Thickness (mm)	Width (mm)		54 V.	45 V.	36 V.	27 V.	18 V.		
30	25	8	+	6.0	4.5	3.0	2.0	1.5	5.4	90
30	25	8	+	5.0	4.0	3.0	2.0	1.3	5.4	92.6
30	28	7.5	-	4.2	3.5	3.0	2.5	2.0	4.3	97.7
30	30	7	+	4.2	3.2	2.5	2.0	1.0	4.3	97.7
30	30	7	+	4.0					3.7	92.5
31	30	7	+	4.0	3.5	3.0	2.0	1.5	3.7	92.5
32	30	7	+	4.0	3.5	2.8	2.0	1.0	4.0	100
32	30	8	-	3.1					4.0	100
33	30	7	+	3.0					4.2	73.8
33	30	7	+	4.0	3.2	2.7	2.2	1.8	4.2	71.4
34	30	7	-	4.0	3.5	3.0	2.0	1.0	4.5	88.9
34	30	8	-	4.0					4.5	88.9
34	30	8	+	4.6					4.8	83.3
34	40	7	-	0.6					4.8	95.8
34	40	7	+	0.5					2.5	24
34	40	7	+						2.5	20

EXHIBIT IV-A



900 First Avenue P.O. Box C King of Prussia, Pennsylvania 19406-0012 • (215) 337-8500

CHEMICALS • EQUIPMENT • HEALTH PRODUCTS

January 30, 1985

Dr. Joseph G. Logan  
Director  
Urban University Center - RAN 200  
University of Southern California  
3716 South Hope Street  
Los Angeles, CA 90007

Dear Dr. Logan:

The conversation you had with Victor Chatigny demonstrates to us the continued excitement there is for users of KYNARE Piezo Film.

We are continually improving our quality assurance procedures and our production techniques so that our products is predictable and consistent. We have now perfected the technique of corona poling the Piezo Film. This allows the film to be poled in longer lengths, at a lower cost, with great consistency of high standards. We have, in the last month, implemented stricter quality control procedures which tracks the activity level of the film. We can add additional verification steps, if required, to qualify the activity of the film at tolerances higher than our normal range.

We are working on some new developments with Piezo Film. One of the most exciting so far has been the development of our new  $VF_2/VF_3$  co-polymer. Not only is the activity level of this new polymer higher, but it is stable to temperatures up to 110°C. In various military applications, this can be very important.

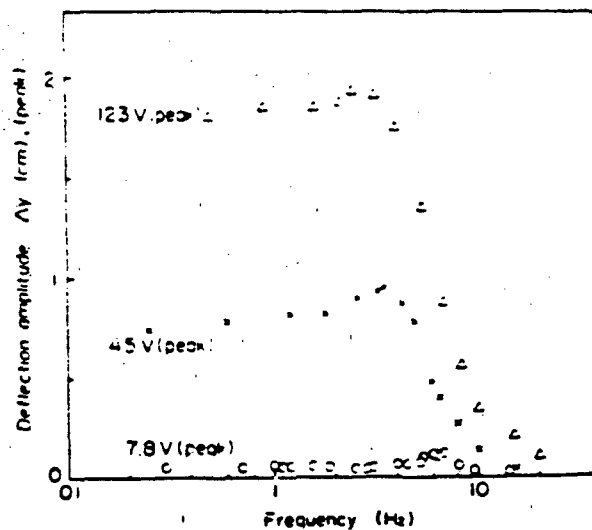
We are looking forward to your continued development. If we can be of further assistance, please feel free to contact us.

Sincerely,

A handwritten signature in dark ink, appearing to read 'Donald L. Halvorsen'.

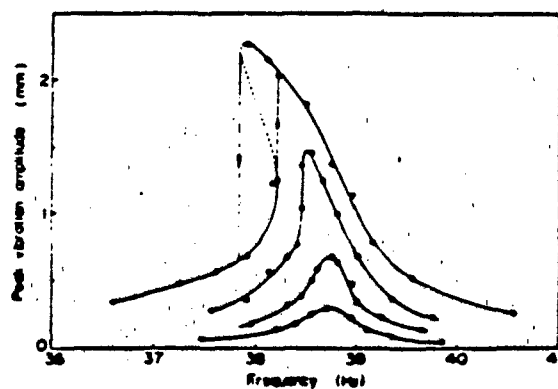
Donald L. Halvorsen  
Sales Engineer  
Piezo Film Department

DLH:ahm



Deflection amplitude versus frequency<sup>2</sup>

FIGURE IV-22



Vibration amplitude of a single layer PVDF cantilever as a function of frequency.<sup>2</sup>

FIGURE IV-23

Two Electrode Configuration

Dimensions

Length - 25mm

Width - 10mm

Thickness - 30 $\mu$ m

Single pulse -  $\pm$  1mm deflection  
at + 20V

Pulse width - 50ms or 1/20 sec

Frequency 10Hz

Test of adhesive - operates after  
three weeks

Voltage	Average Deflection (mm)	
2 Volts	< 0.5	0.09 *
4 Volts	< 1.0	0.19
6 Volts	$\approx$ 1.0	0.28
8 Volts	2.0	0.38
10 Volts	3.0	0.48

\* Static Deflection

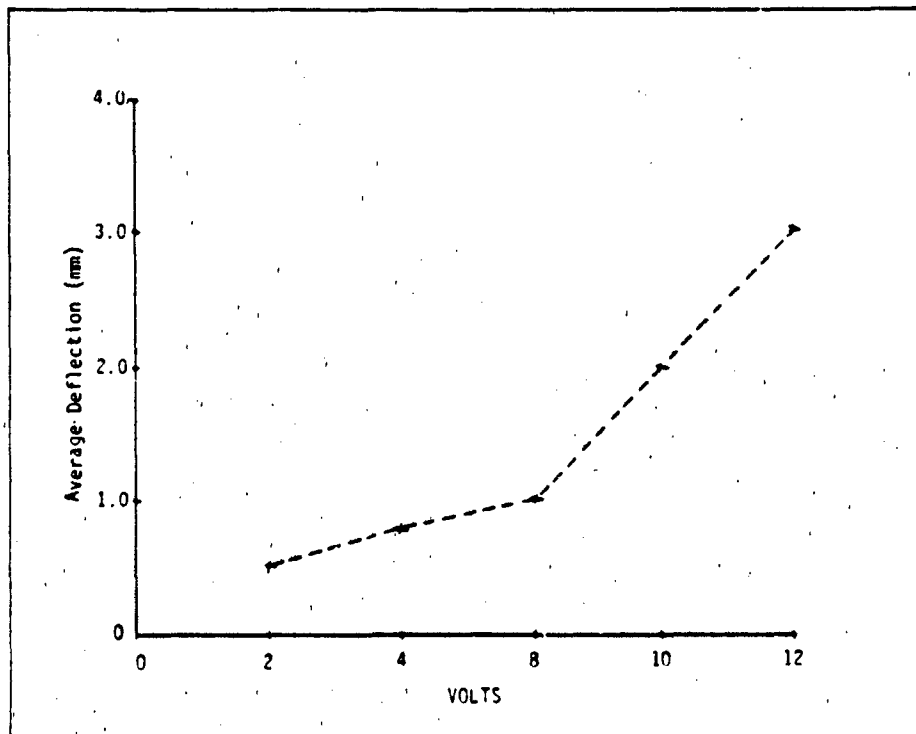


FIGURE IV-24

### Three Electrode Configuration

#### Dimensions

Length - 25mm

Width - 10mm

Thickness - 30µm

Frequency - 10Hz

Deflection of 1mm when width  
is reduced from 0.5 to 10ms  
or 1/10 of pulse width.

Static deflection - 2mm +

Pulse width - 1/10 sec

Voltage	Average Deflection (mm)	
4 Volts	1.0	0.19*
8 Volts	2.0	0.38
12 Volts	4.0	0.57
16 Volts	5.0	0.77
20 Volts	6.0	0.96

\* Static Deflection

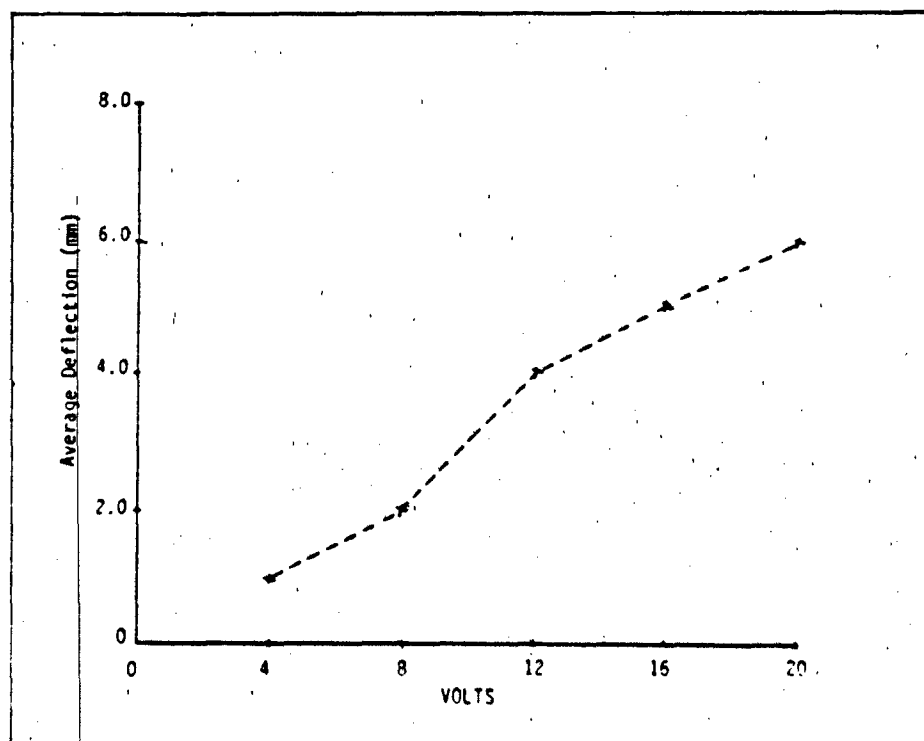


FIGURE IV-25

### Three Electrode Configuration

#### Dimensions

Length - 13.5mm

Width - 9.0 mm

Thickness - 30 $\mu$ m

Pulse width -  $1.25 \times 5\text{ms} = 6.25\text{ms}$

Pulse length - 20V

Cycle time -  $5.2 \times 5 = 26\text{ms}$

Frequency - 38.45Hz

Ratio pulse width to cycle

time =  $(1/6.25)/(26) = 0.24$

Voltage	Average Deflection (mm)	
4 Volts	0.5	0.05*
8 Volts	1.0	0.11
12 Volts	1.5	0.16
16 Volts	2.4	0.22
20 Volts	3.0	0.28

\* Static Deflection

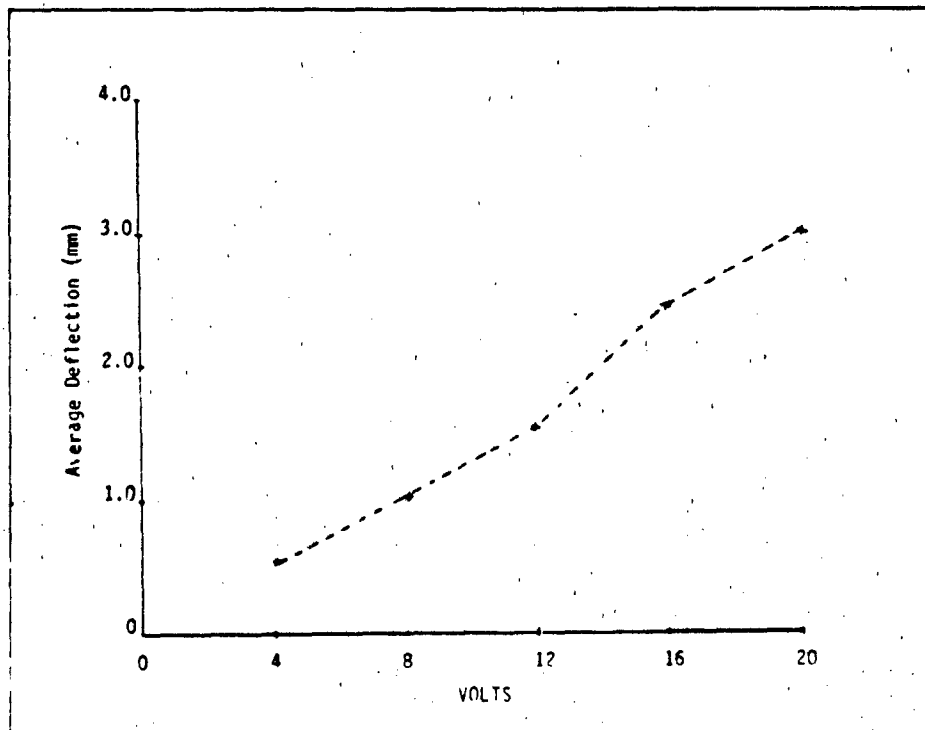


FIGURE IV-26

- Two Electrode Configuration

Dimensions

Length - 13.5mm

Width - 9.0mm

Thickness - 30 $\mu$ m

Deflection at 54 volts = 1.0mm

Decaying time vs. deflection

Time (s)	Average Deflection (mm)
0	1.0
1.0	0.75
2.0	0.50
3.0	0.25
4.0	0.12

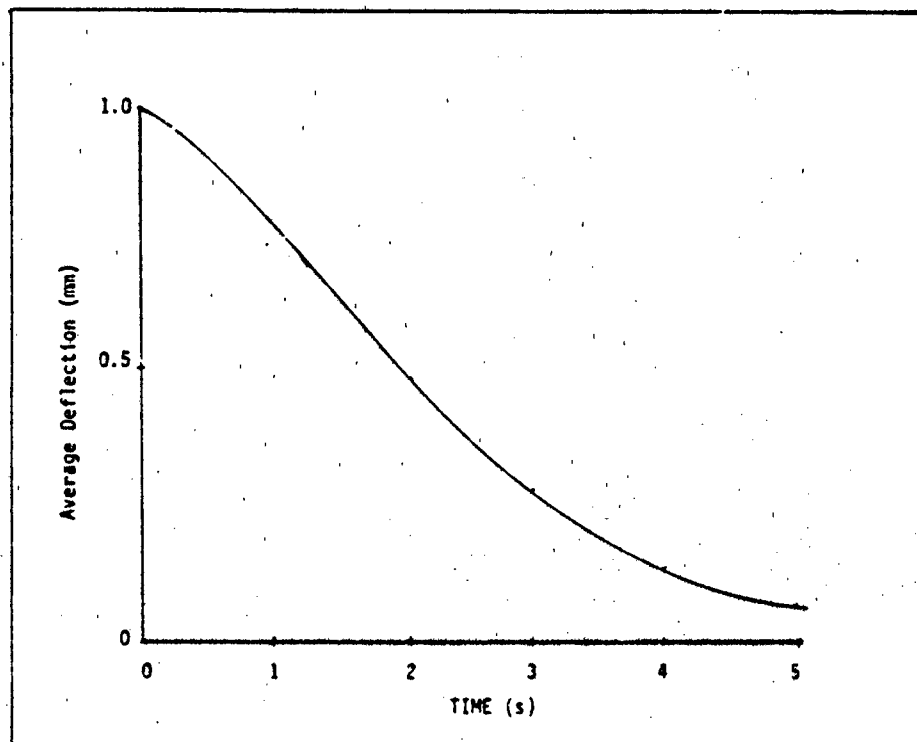


FIGURE IV-27

### Two Electrode Configuration

#### Dimensions

Length - 13.5mm

Width - 9.0mm

Thickness - 30 $\mu$ m

Method for accurately determining  
storage capability decay

Applied voltage - 18, 27, 36, 45  
and 54 volts

Time (s)	Average Deflection (mm)
0.0	1.0
1.30	0.6
2.44	0.6
4.30	0.4
5.70	0.4

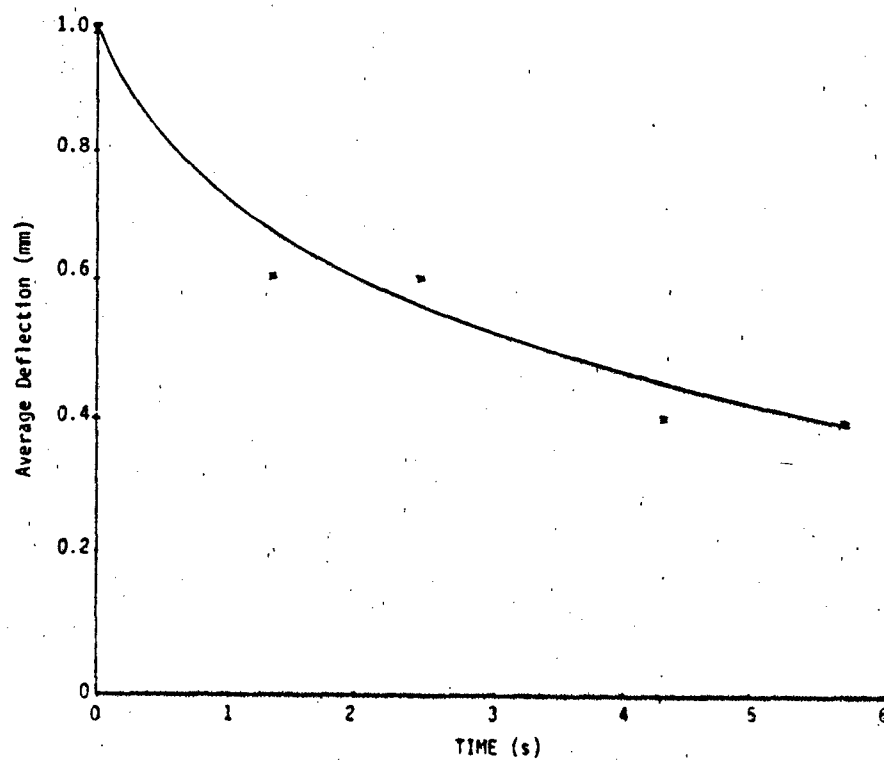


FIGURE IV-28

Three Electrode Configuration

Dimensions

Length - 25mm

Width -

Thickness - 30 $\mu$ m

Deflection at 54 volts = 1.5mm  
Decaying time vs. deflection

Time (sec)	Average Deflection (mm)
0	1.5
1.0	0.5
2.0	0.25
3.0	0.12
4.0	0.06
5.0	0.0

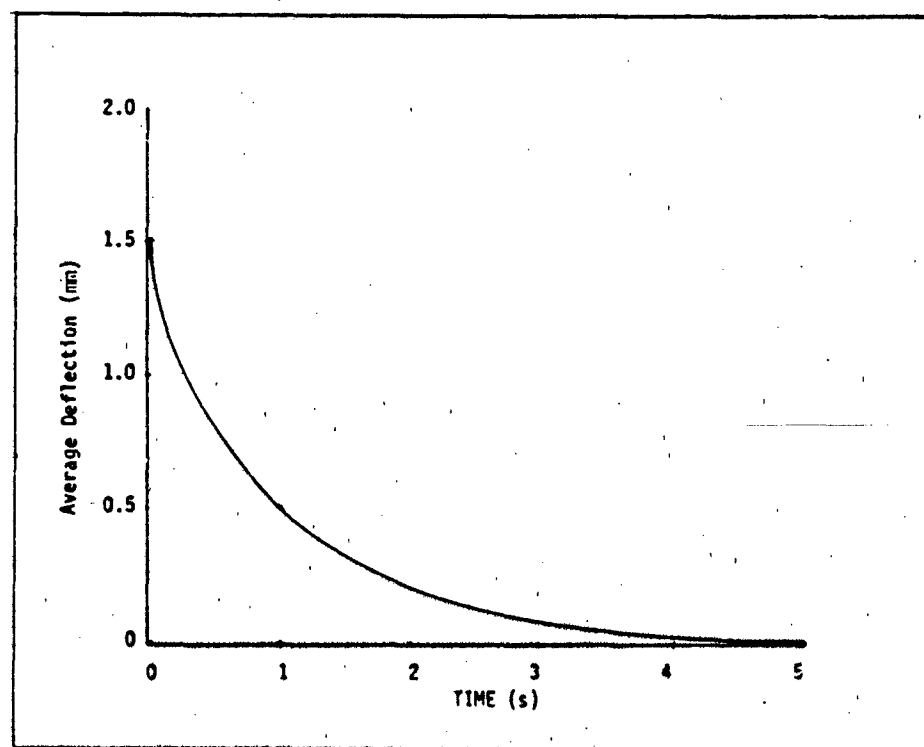


FIGURE IV-29

### Two Electrode Configuration

#### Dimensions

Length - 13.5mm

Width - 9.0mm

Thickness - 30µm

Effect of increasing voltage  
results in increasing displacement  
and decreasing voltage by steps  
decreases displacement

Voltage	Average Deflection (mm)
9 Volts	0.1
18 Volts	0.2
27 Volts	0.4
36 Volts	0.6
45 Volts	0.8
54 Volts	1.0
45 Volts	0.8
36 Volts	0.6
27 Volts	0.4
18 Volts	0.2
9 Volts	0.1

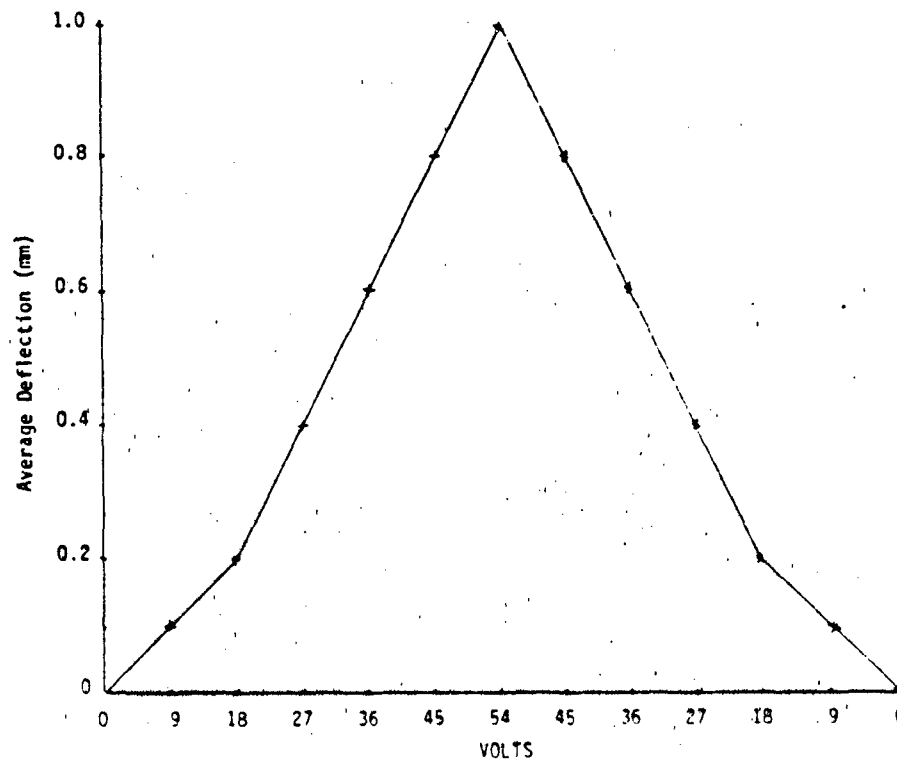


FIGURE IV-30

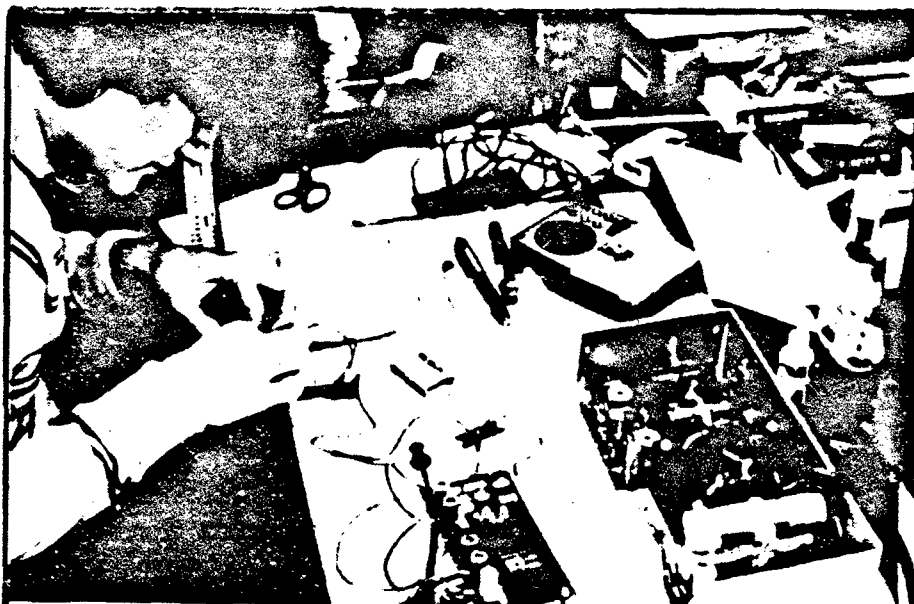


FIGURE IV-31

Fabrication of  
PVDF film  
Bimorphs

FIGURE IV-32

Testing of PVDF  
film Bimorphs  
with chopped DC  
voltage



FIGURE IV-33

Testing of PVDF film Bimorphs  
with AC voltage

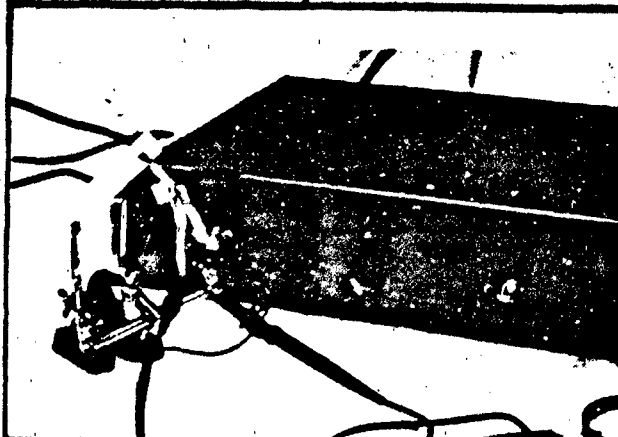




FIGURE IV-34

AC Pixel Tests



FIGURE IV-35

Pulsed DC Pixel  
Driver Tests

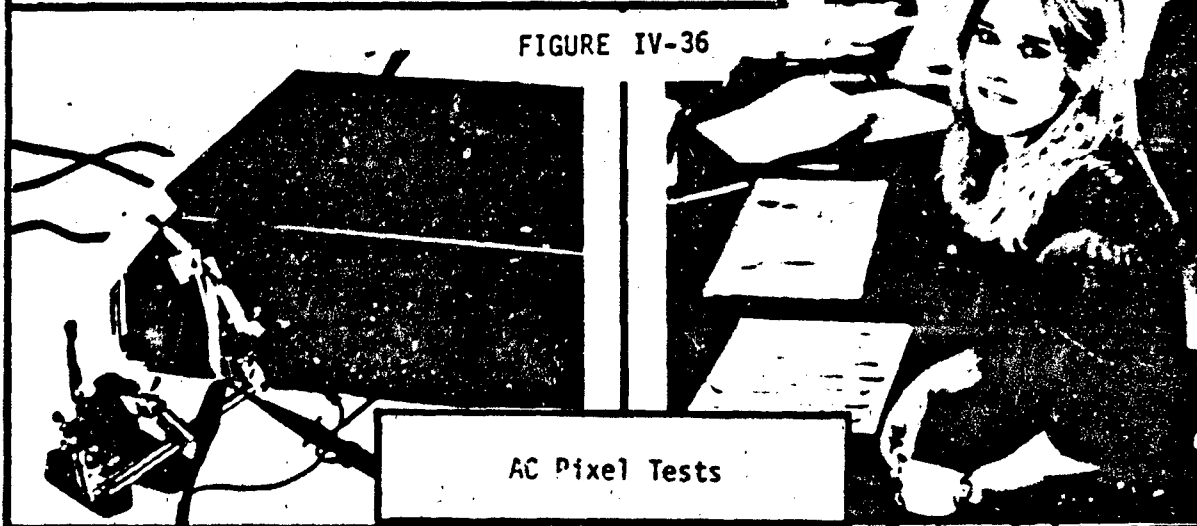


FIGURE IV-36

AC Pixel Tests

FIGURE IV-37

Testing of PVDF  
film Bimorphs  
with chopped DC  
voltage



FIGURE IV-38

AC Bimorph Tests

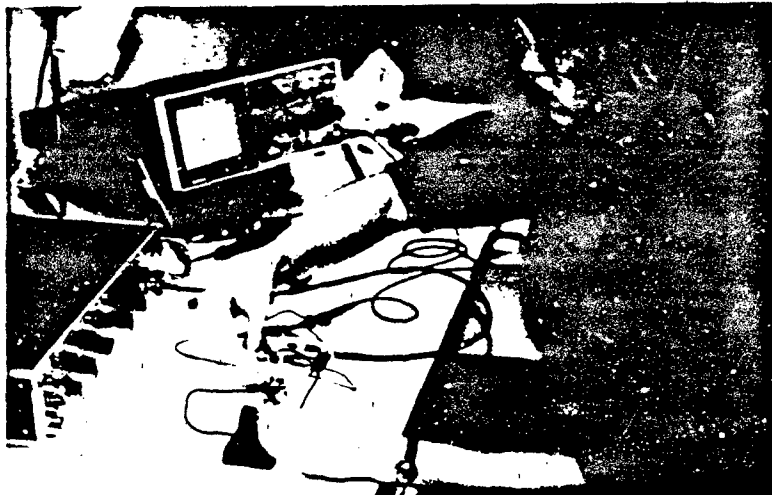


FIGURE IV-39

fabrication of  
PVDF film  
Bimorphs



#### 4. PROTOTYPE DESIGN

##### a. Optical Valve Configurations

Tests of the two and three electrode bimorph configurations suggest that unique display systems can be developed. As shown in Figs. 27 and 28, the two electrode configurations operated with pulsed dc voltage exhibits very slow leakage and consequently can function as a pixel element with a memory capability.

Since construction of the 2 electrode configuration also presents simpler fabrication problems, this configuration was utilized as the basis of the design of the pixel elements, the optical valves for display applications. A number of simpler applications can easily be visualized as will be indicated.

The primary motivation for this SBIR Program was the development of a large-scale, high resolution, multicolor software display to proof and display maps and charts.

The deflection phenomena exhibited by the two-electrode piezoelectric bimorphs, suggested that optical valve pixel elements constructed using these bimorphs could satisfactorily fulfill the requirements for the fabrication of displays to satisfy the Army requirements.

Based on the use of the two and three electrode bimorphs, a number of different pixel configurations were developed for display applications.

These elements can be utilized as the basis for the development of a simple flat screen, large, wall-mounted display system for computer applications that would be superior to existing systems. The computer display unit should be superior to the unit indicated in Exhibit II-A. Electronic blackboard operations are also suggested, since the requirements for an electronic blackboard are identical with the requirements for computer monitor display. Incorporating a tablet with a computer system enables the development of a hand-written, large screen display capability.

Typical applications are summarized in Table 11.

One of the objectives of the design was to achieve a display capability at voltage levels of approximately 20 volts, levels at which inexpensive CMOS technology could be utilized. As was indicated in Figs. 14 to 17, for nominal lengths of the bimorph, 25 to 30 mm, the deflections would be of the order of 1 mm or less. Since the objective is to develop an optical valve, modulation of light beams at this displacement level can only be achieved if pixel dimensions of 1 mm or less are utilized or if simple lens configurations are utilized to focus the light beams for each individual pixel element. Examples of the various types of pixel configurations that can be developed are shown in Figs. 40 to 49.

The simplest configurations shown in Figs. 40-41 consist simply of a baffle plate to confine the light of a given pixel area, with the light modulated by a single bimorph or a pair of bimorphs. With this simple configuration, black/white on-off displays can easily be constructed. Such displays could function as billboards, computer monitors, electronic blackboards, etc., and can be

TABLE IV-11

Application	Bimorph	Film	Operational Mode	Operating Voltage	Remarks
Map Display *	2-electrode	6 micron 9 micron 16 micron	DC Color	20 - 60V	Color display lens plate, 500-1000 line, pixel memory required, slow scan
Computer Monitor	2-electrode	6 micron 9 micron 16 micron	DC Black and White	20 - 90V	Black & White slow scan, on-off display 300-500 lines, no lens plate, pixel memory.
Computer Monitor	2-electrode	6 micron 9 micron 16 micron	DC Color	60 - 90V	Color display, no lens plate, 300-lines, on-off display, pixel memory, slow scan
Electronic Blackboard	2-electrode	6 micron 9 micron 16 micron	DC Black and White	60 - 90V	Black & White, on-off display 300-500 lines, no lens plate, pixel memory, slow scan
Detailed Map Display	2-electrode	6 micron 9 micron	DC Color	20 - 60V	Grey scale, color display, 500-1000 lines, pixel memory, slow scan, lens plate
TV, VCR Display	3 electrode	6 micron 9 micron	AC Color	20 - 90V	Potential application for line-at-a-time scan, pixel frequency 60 Hz., grey scale, voltage amplitude established by minimum charging time for bi-morph to produce resonant response.

\* Minimum flat panel screen size for 0.25 sq. cm pixel, 1.75 meters x 2.63 meters for 525 lines.

developed at very small cost. Pixels with dimensions 0.5cm x 0.5cm are easily fabricated. Color backgrounds are easily introduced (black or color, etc.).

For more detailed displays, requiring a grey-scale capability, simple lens configurations can be utilized, Figs. 42-49. Simple inexpensive plastic lenses of a quality sufficient to provide the required focusing capability can be utilized. These lenses are easily molded by injection molding techniques.

#### b. Display System Configuration

A test bed was designed, Fig. 50, to enable testing of the different pixel configurations. The design was such that the critical elements, the baffle plates, the lens plates, the pixel modulation plates (the bimorph element plates), etc., Figs. 51-58, could easily be inserted in the prototype test facility, Fig. 59.

Full color representation is achieved simply by use of appropriate color filters as indicated in Figs. 58 and 59. The actual values of relative brightness that have been adopted in use of television, using white as 100% brightness are:

Green	59%
Red	30%
Blue	11%

The brightness of each color element is easily controlled by the voltage applied to the bimorph and the three primary colors can easily be mixed to generate the appropriate colors. A schematic of the design for reproduction of the color signals is shown in Fig. 60. The color filters can be inserted between the light source and the first lens or after the last lens in front of the screen.

The conventional television system utilizes a three dot matrix as indicated in Fig. 60. It is anticipated that the four element configuration, Fig. 60 will be more appropriate for use with display devices based on mechanical modulation schemes. The additional pixel enables a greater flexibility in that white light can be utilized in the fourth element of the matrix or other color elements can be employed to more easily achieve the required relative color brightness. Further as indicated in Fig. 49, the color elements can be superposed and color representation might be achievable that equal or surpass current TV systems.

#### c. Matrix Address System

A matrix address system, Figs. 59-60 was designed easily capable of driving an 8 x 8 array of elements. This design can be expanded to handle larger array sizes.

The heart of the circuit is an Intel 8088 microprocessor, the same processor used in the IBM Personal Computer. It features a sixteen bit internal architecture with an eight bit data bus to simplify interfacing to other devices. The use of a microprocessor to control the circuit allows modification to the timing waveforms without monumental changes in the circuitry.

The system design includes 8K bytes of eraseable programmable read-only memory (EPROM) which is used to store the microprocessor's program. An IBM Personal Computer is used to program the EPROM. Should there be a need for modifications, the EPROM can be erased by exposing it to ultra-violet light and then reprogrammed. The part used is the 2764.

For the temporary storage of information by the microprocessor, 2K bytes of random access memory (RAM) is provided. Although 2K of RAM is much more than required, there is space capacity for up to 8K bytes of RAM without significant changes in hardware. The RAM consists of an HM6116.

Other peripherals attached to the microprocessor are the keyboard interface, the programmable timer, the interrupt controller, and the piezo-electric pixel element interface.

The keyboard interface allows for communication between the user and the microprocessor. It consists of an 8 bit driver and an 8 bit receiver which are under direct microprocessor control. It can handle a 64 key keyboard wired in an 8x8 matrix. The processor reads the keyboard by sending a signal to one of the bits of the driver and checking the receiver to see which of the received 8 bit contains a response.

The programmable timer serves as an "alarm clock" for the microprocessor. The microprocessor programs the timer for a predetermined time interval and the timer then informs the microprocessor when that time interval has passed. This gives the microprocessor a way to time its activities while remaining free to do other things. The timer used is the 8253.

Both the keyboard interface and the programmable timer obtain the attention of the microprocessor via the interrupt controller. The interrupt controller keeps track of legal interrupt requests their relative priority. The interrupt controller can then issue an interrupt to the microprocessor which the processor can acknowledge or ignore.

The pixel element interface controls up to 64 pixel elements organized in an 8x8 matrix. The interface consists of two types of drivers. The first type is the source-side driver. The source-side driver ties one side of the pixel element to 20 volts when activated, and to ground through a 2K resistor when deactivated. The driver consists of an 8 bit latch to save the state of the pixel, one transistor to translate the signal level from +5 volts to +20 volts, and a second transistor to drive the pixel element. The source-side drivers are used to drive the rows of the pixel array.

To drive the columns of the pixel array, the sink-side drivers are used. The sink-drivers tie the other side of the pixels to ground when activated and are open circuit when deactivated. The sink-side driver consists of an 8 bit latch to save the state of the pixel and a transistor to drive the pixel element. Both source-side and sink-side drivers are under the direct control of the micro-processor.

The circuit is currently designed to scan 8 rows of the pixel array while activating the appropriate columns for the character currently being displayed. Each row remains activated for approximately 0.1 seconds before the row is deactivated and the next row is activated. During the time where the microprocessor is counting off 0.1 seconds, it is also scanning the keyboard for a pressed key. If a key is pressed, the processor leaves the display scanning activity to determine the next character to display. The microprocessor then waits for the key to be released before returning to the display scanning activity.

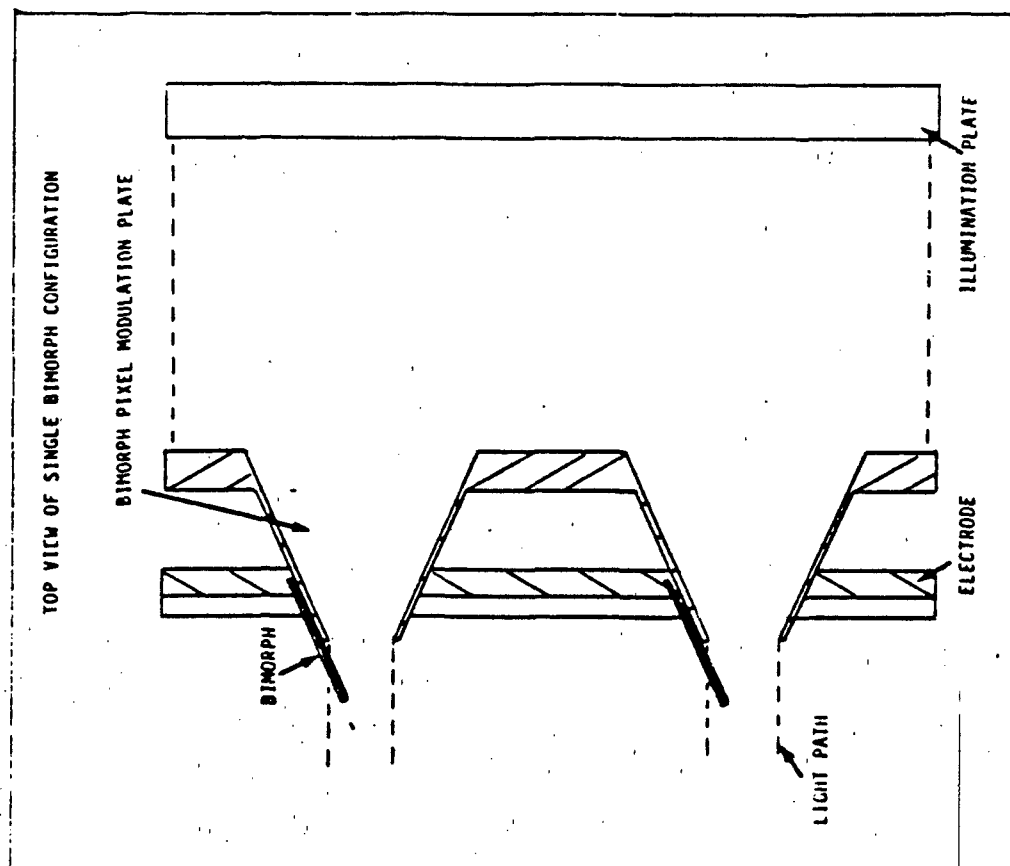


FIGURE IV-40

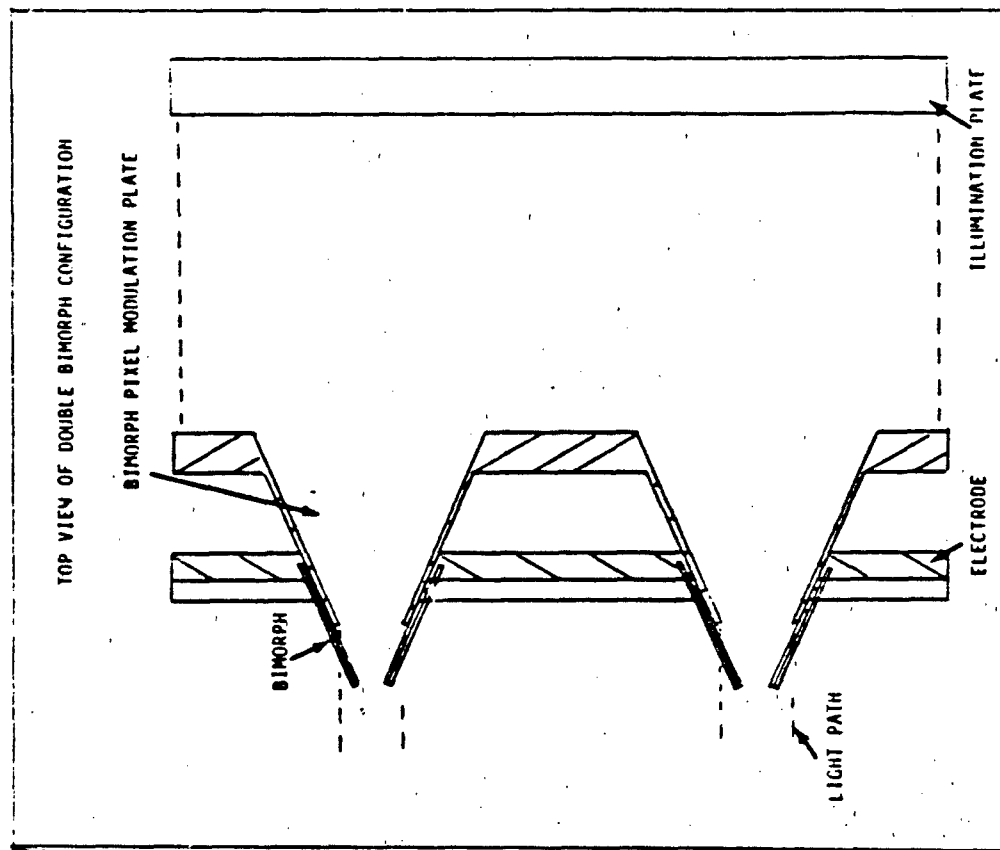


FIGURE IV-41

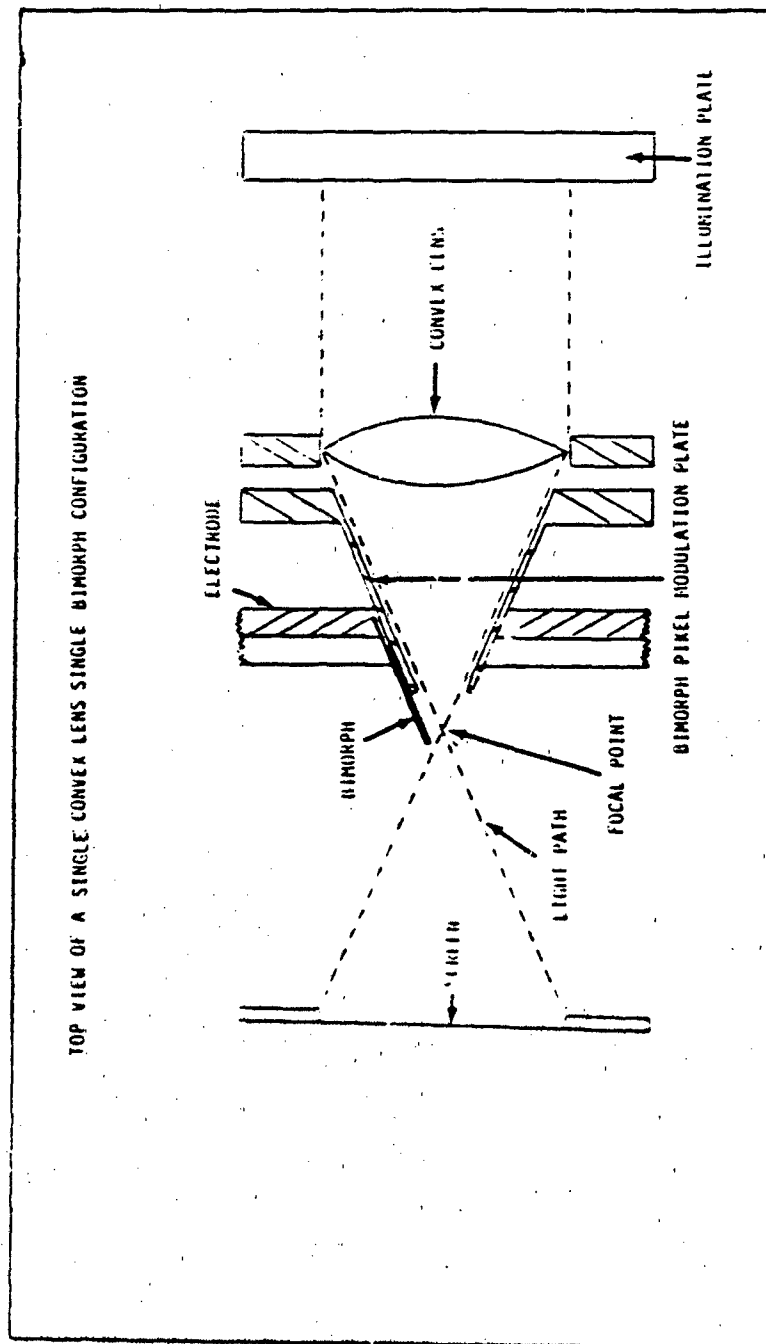


FIGURE IV-42

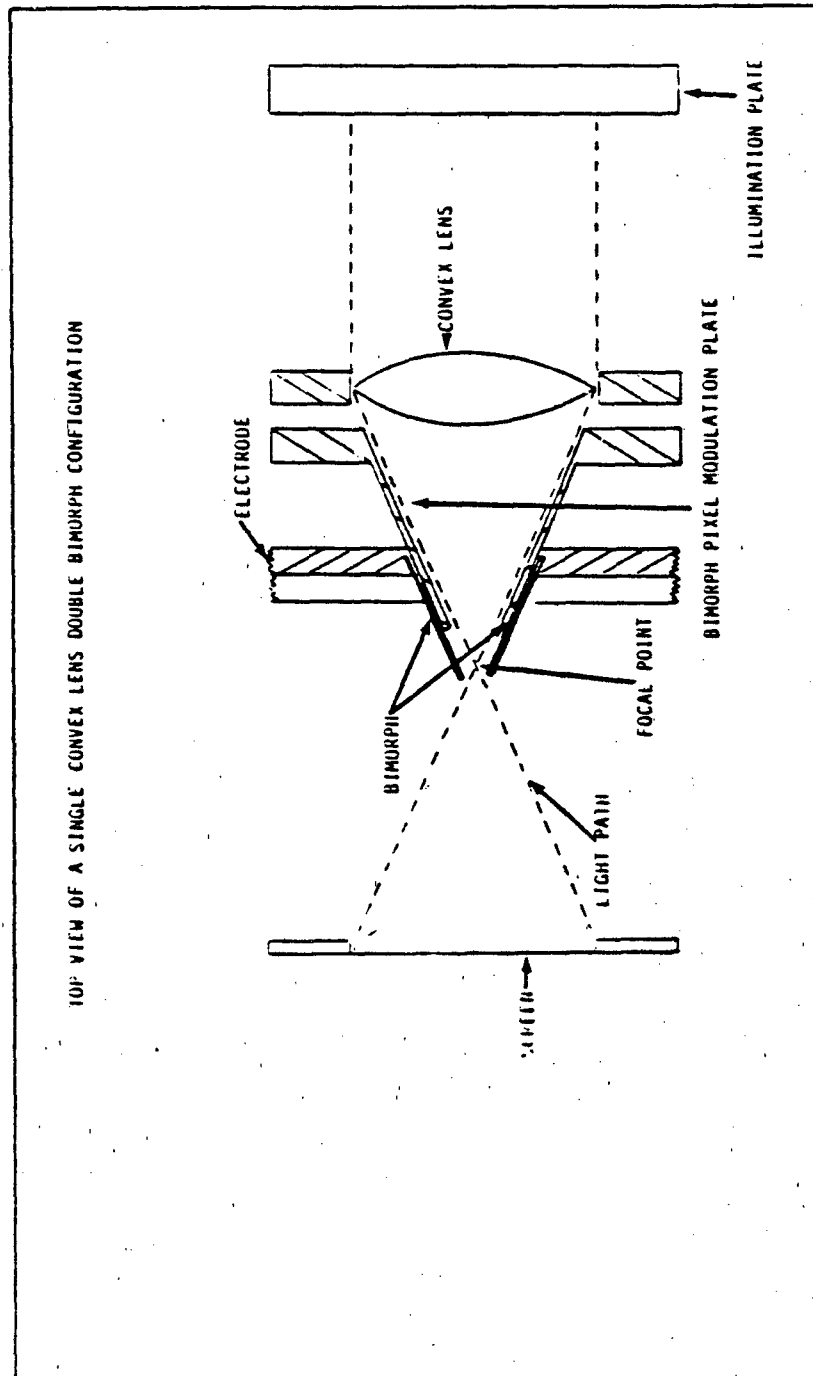


FIGURE IV-43

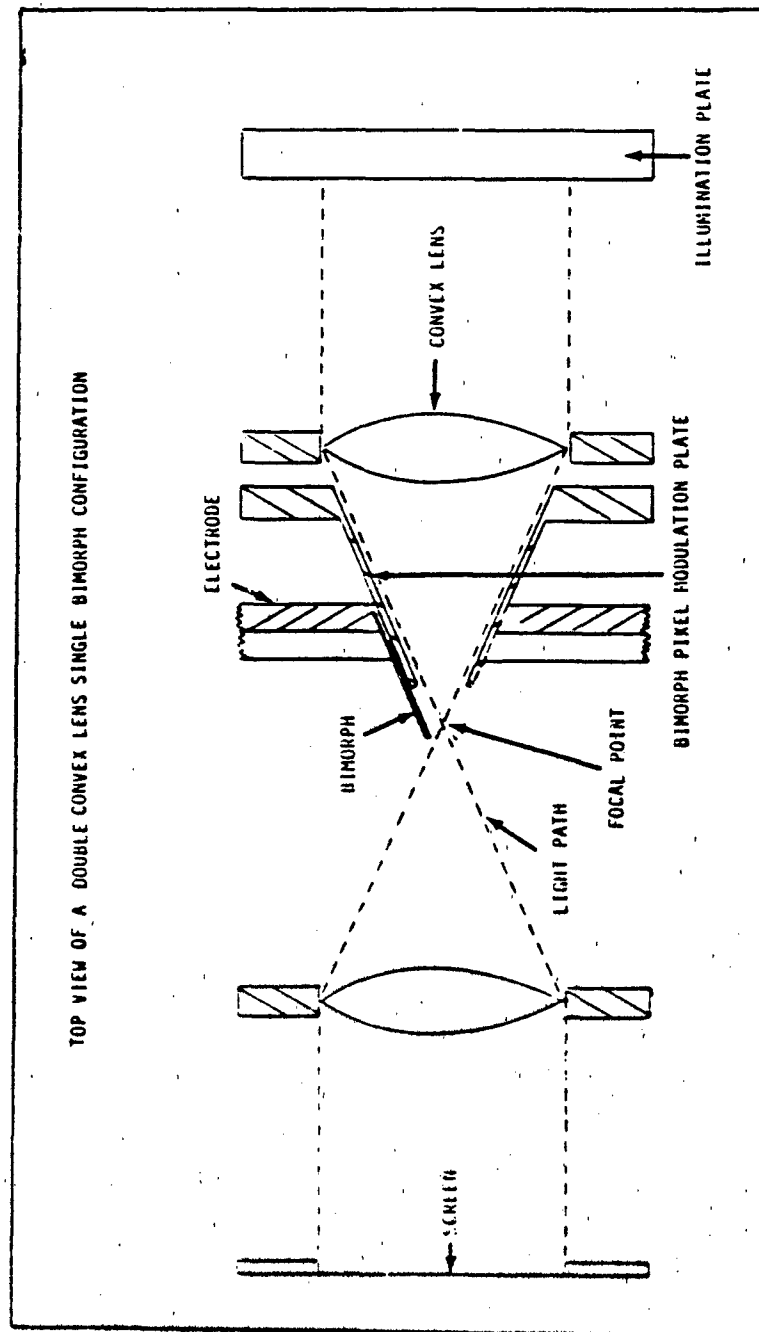


FIGURE IV-44

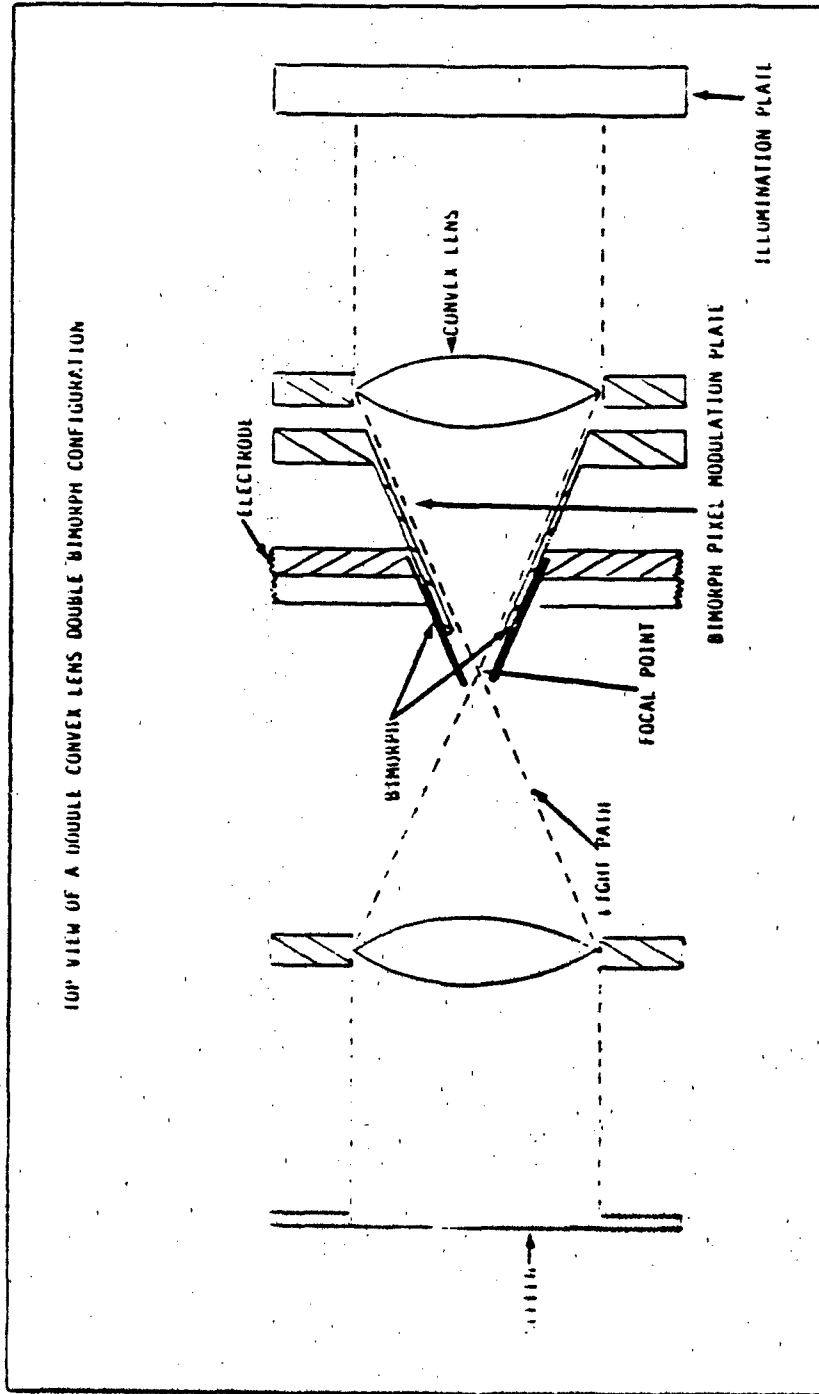


FIGURE IV-45

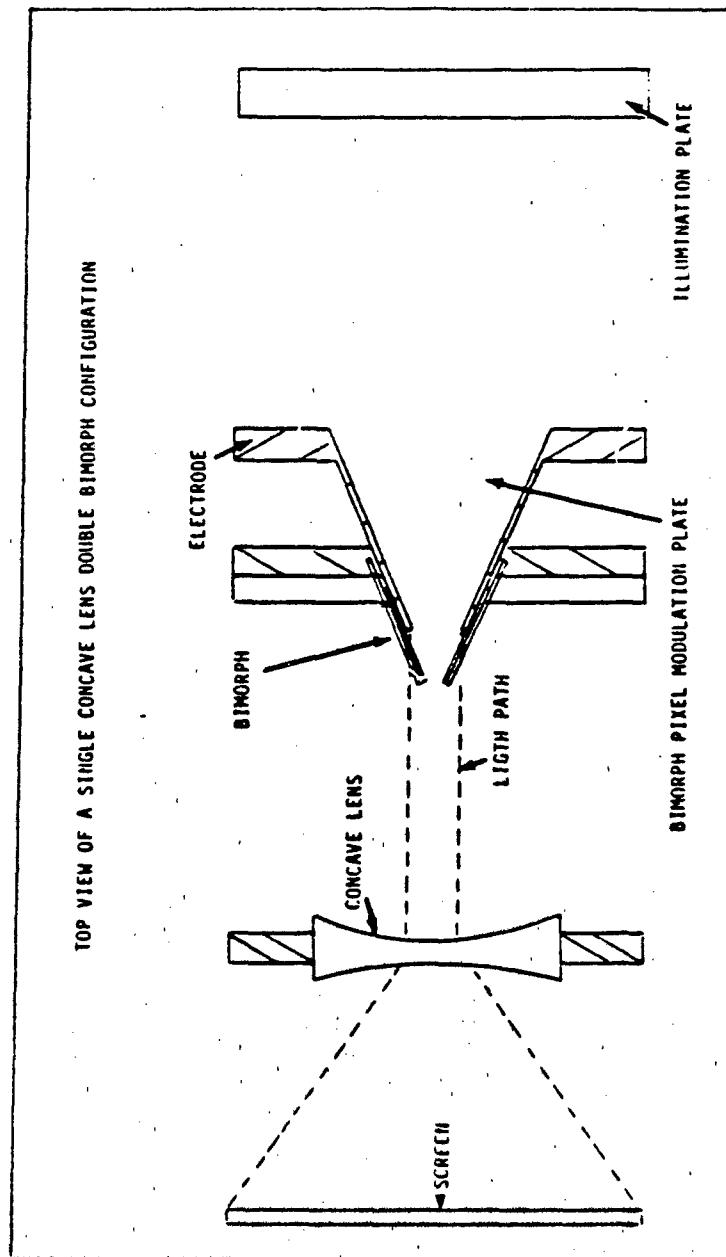


FIGURE IV-46

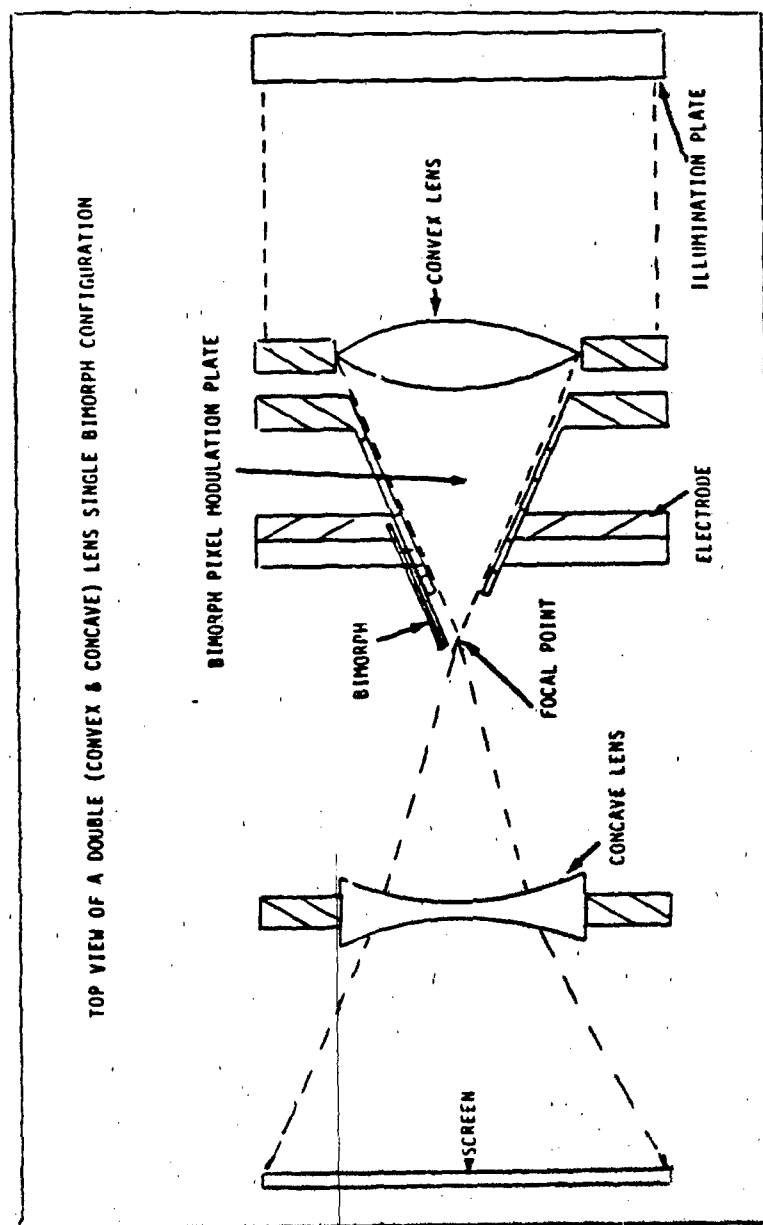


FIGURE IV-47

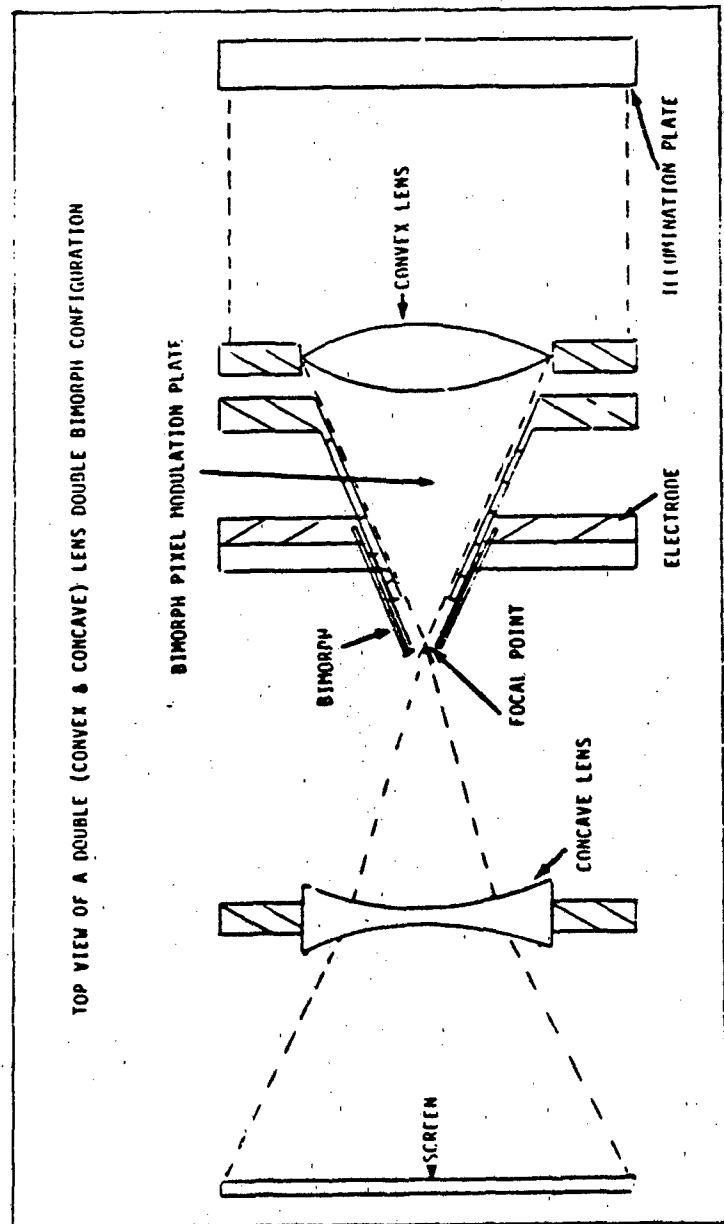


FIGURE IV-48

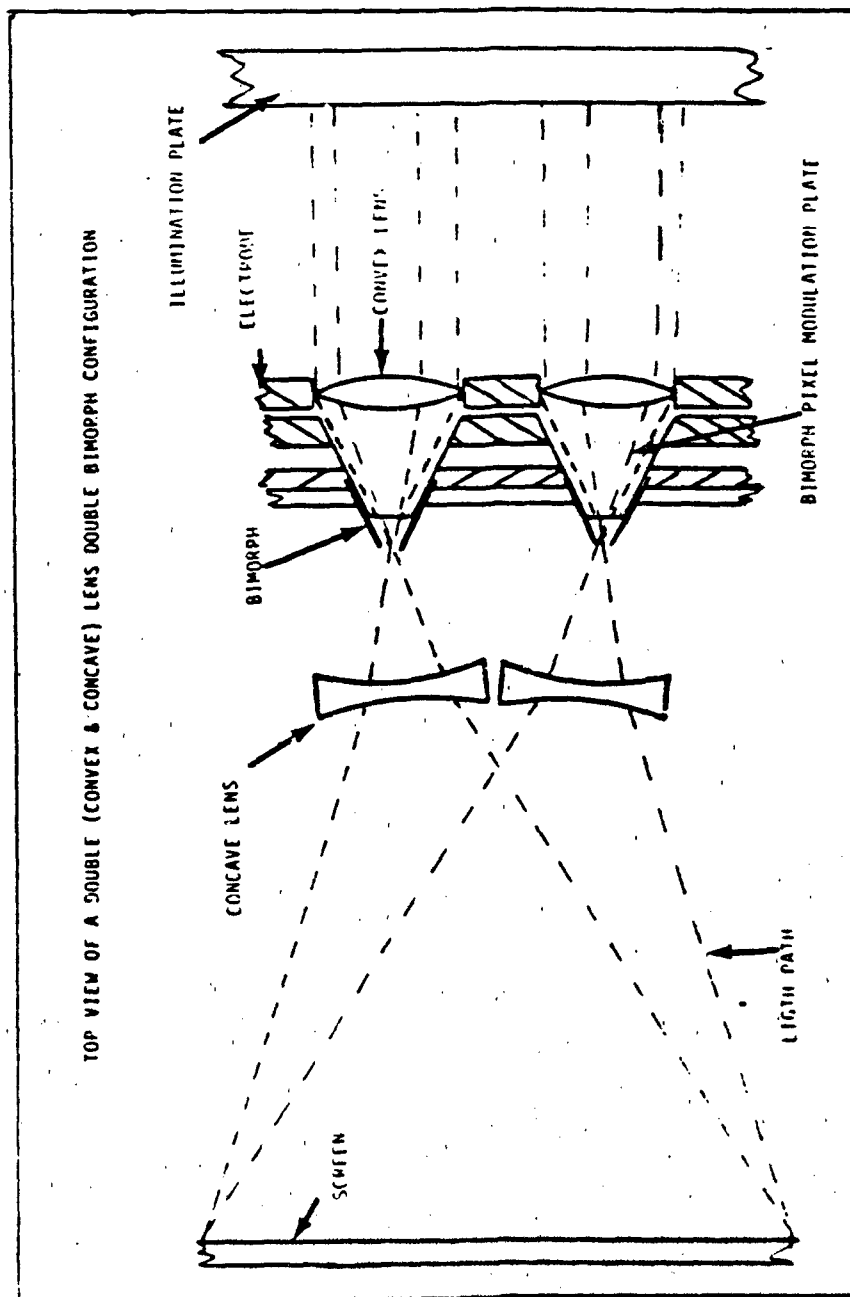


FIGURE IV-49

SCALE - 1/8 SIZE

FLAT PANEL DISPLAY  
TEST CONFIGURATION

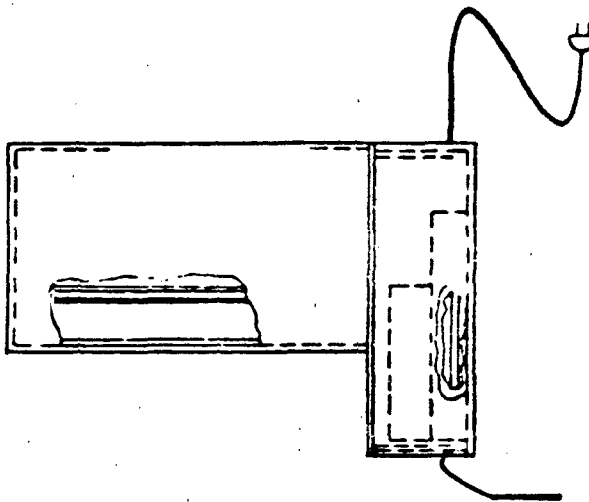
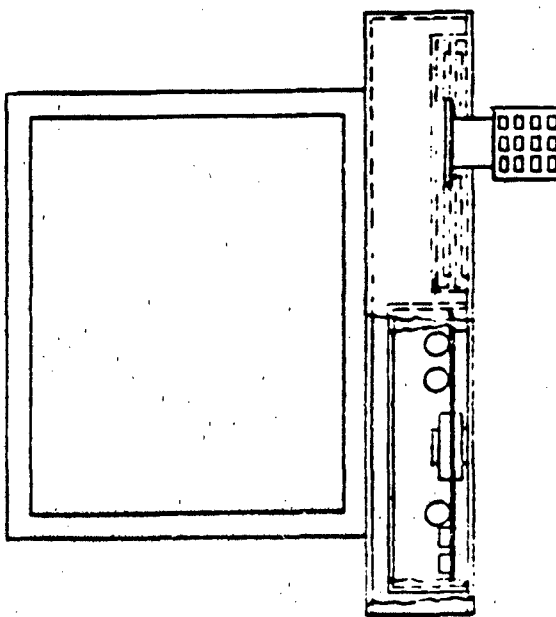
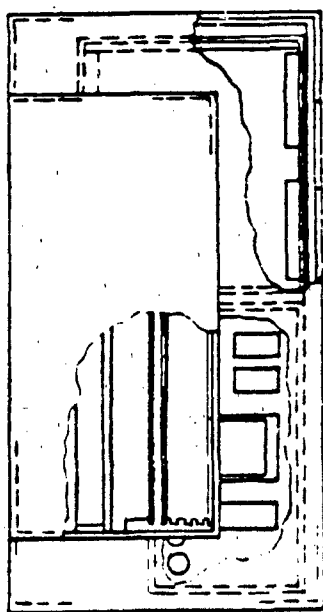


FIGURE IV-50

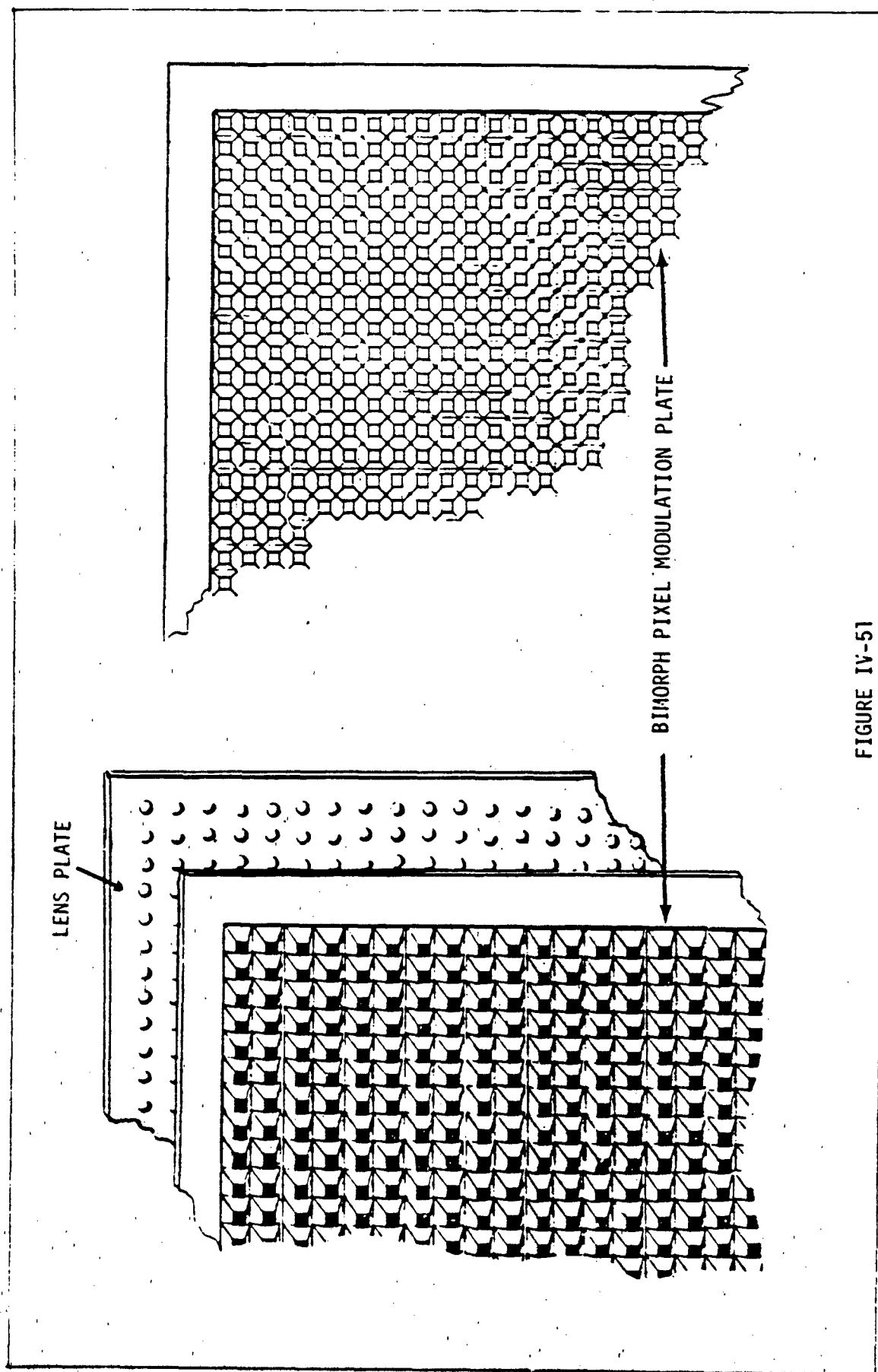


FIGURE IV-51

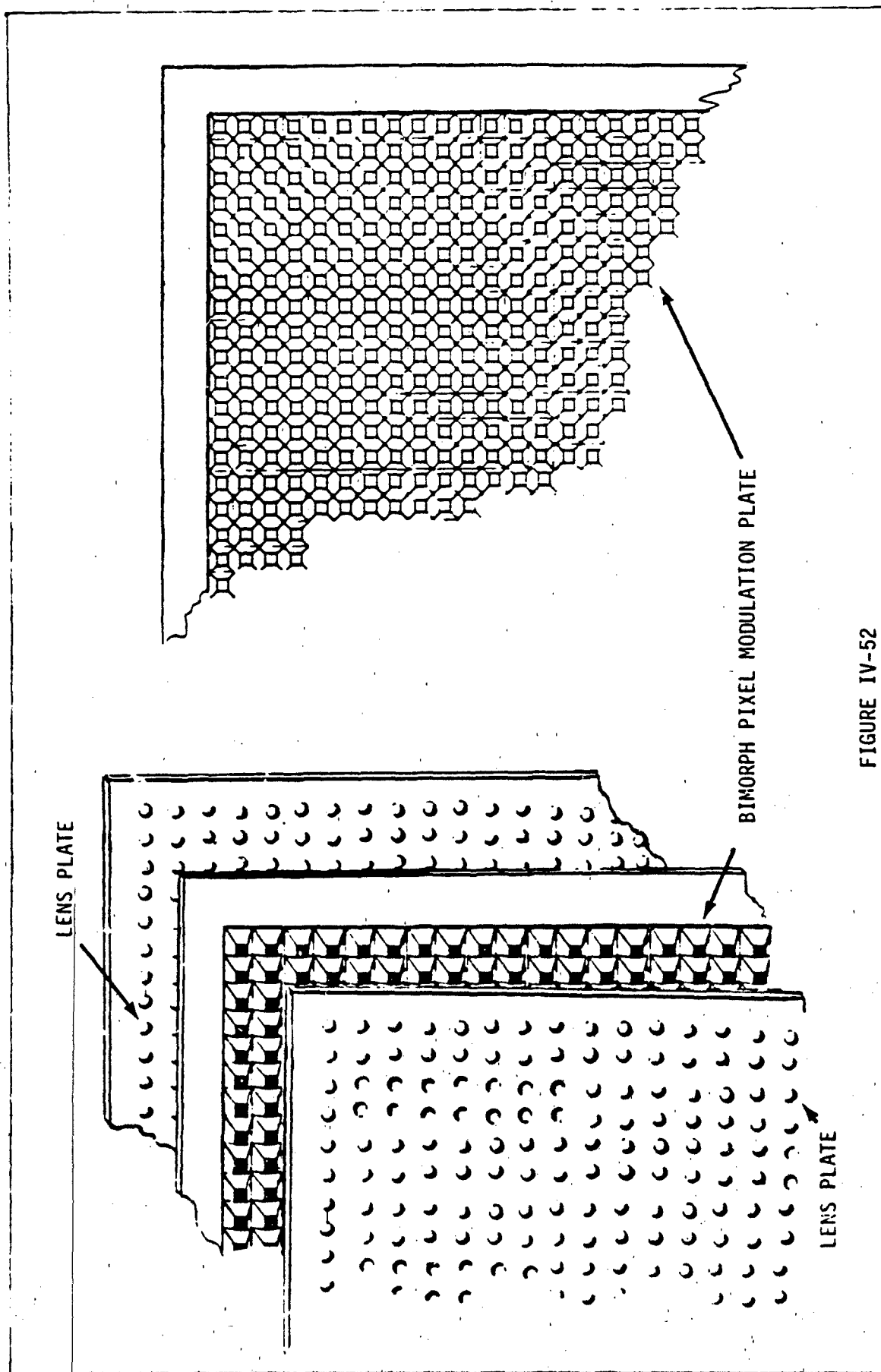


FIGURE IV-52

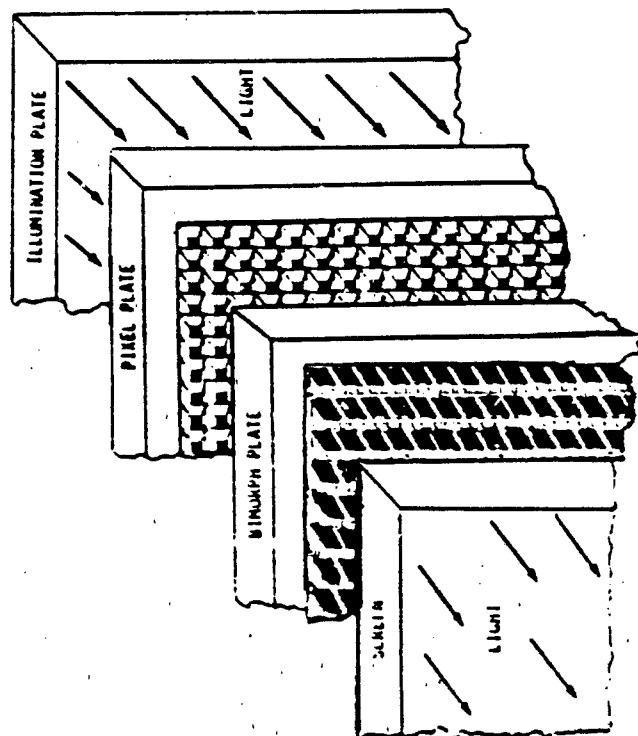


FIGURE IV-53

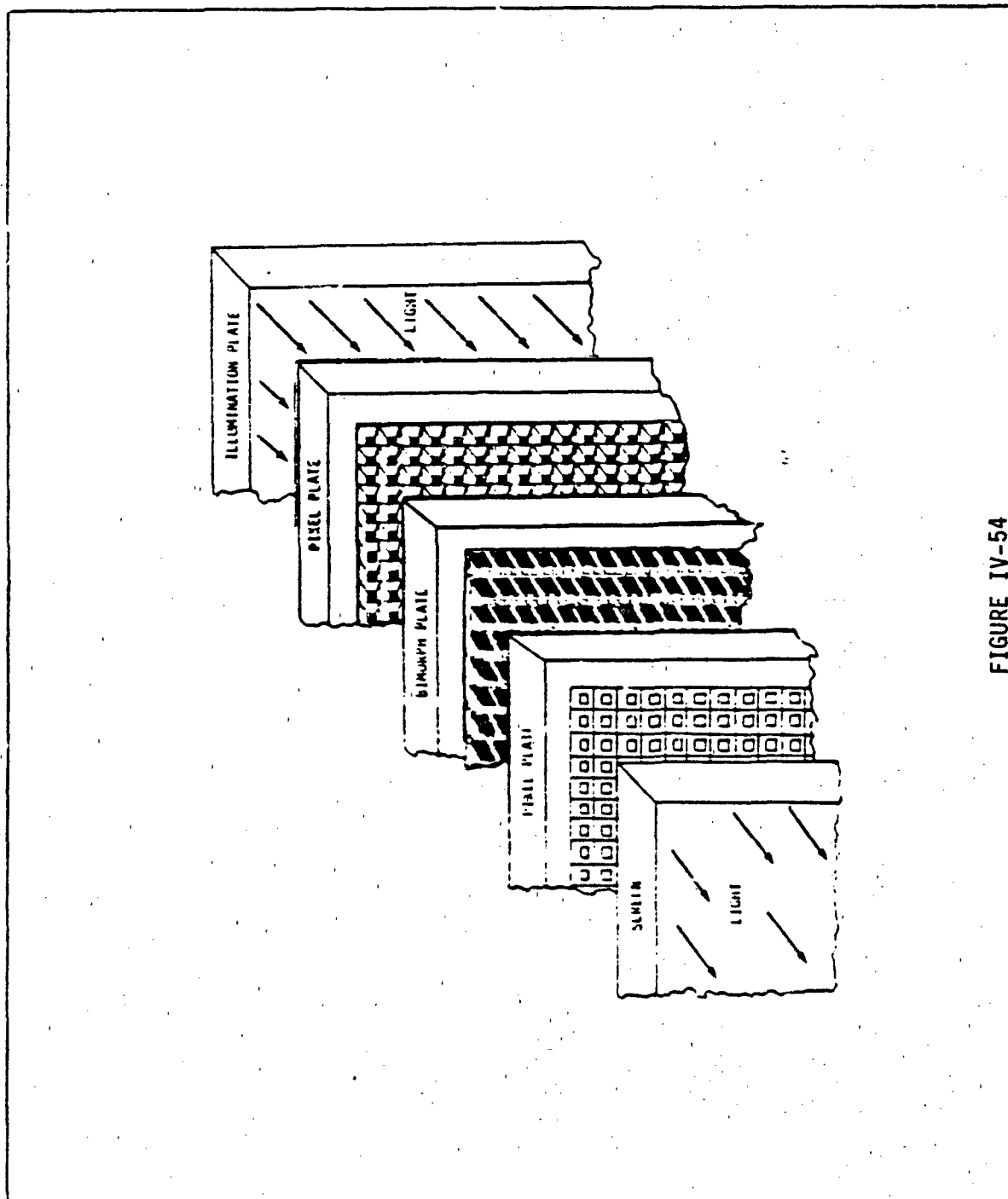


FIGURE IV-54

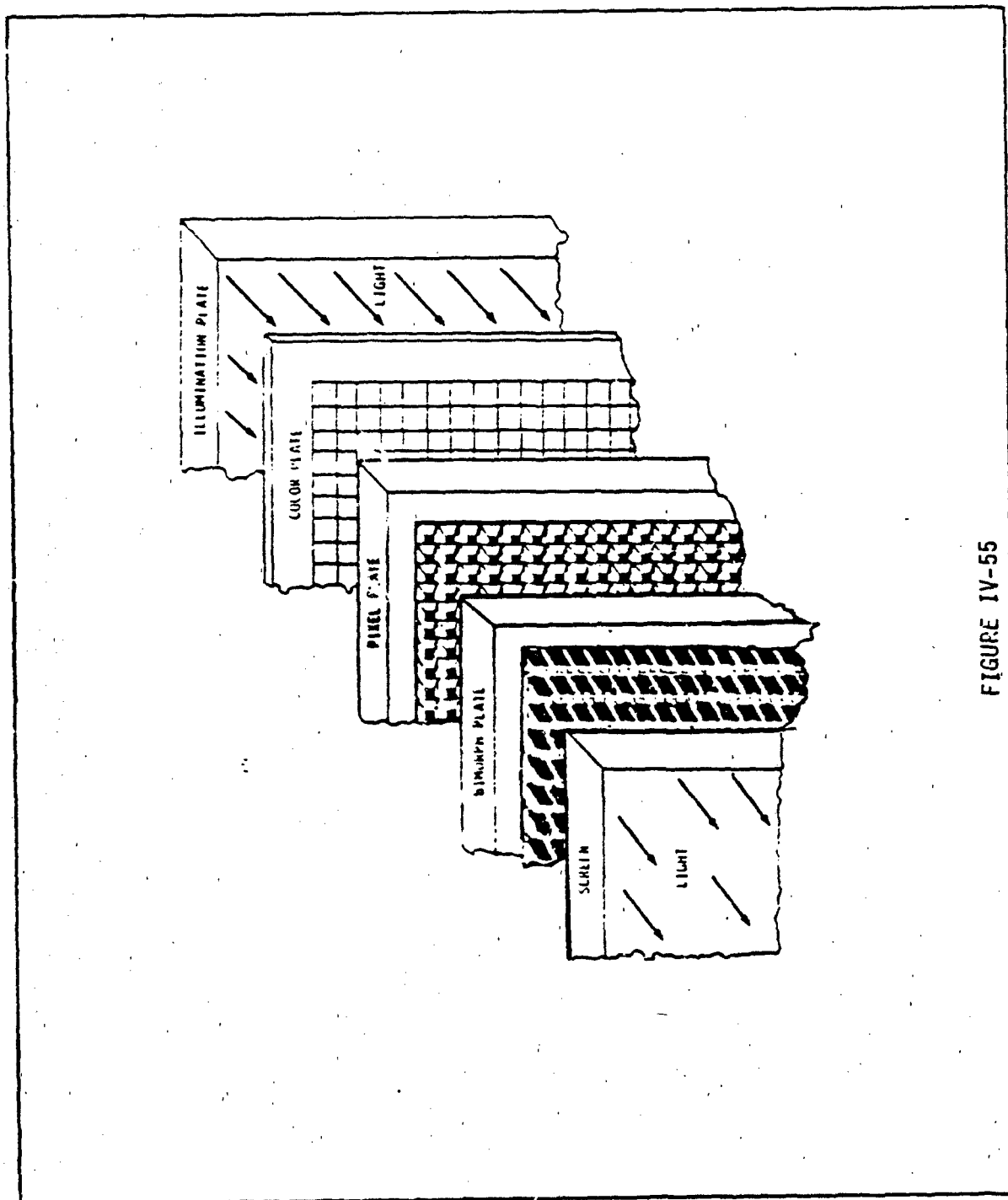


FIGURE IV-55

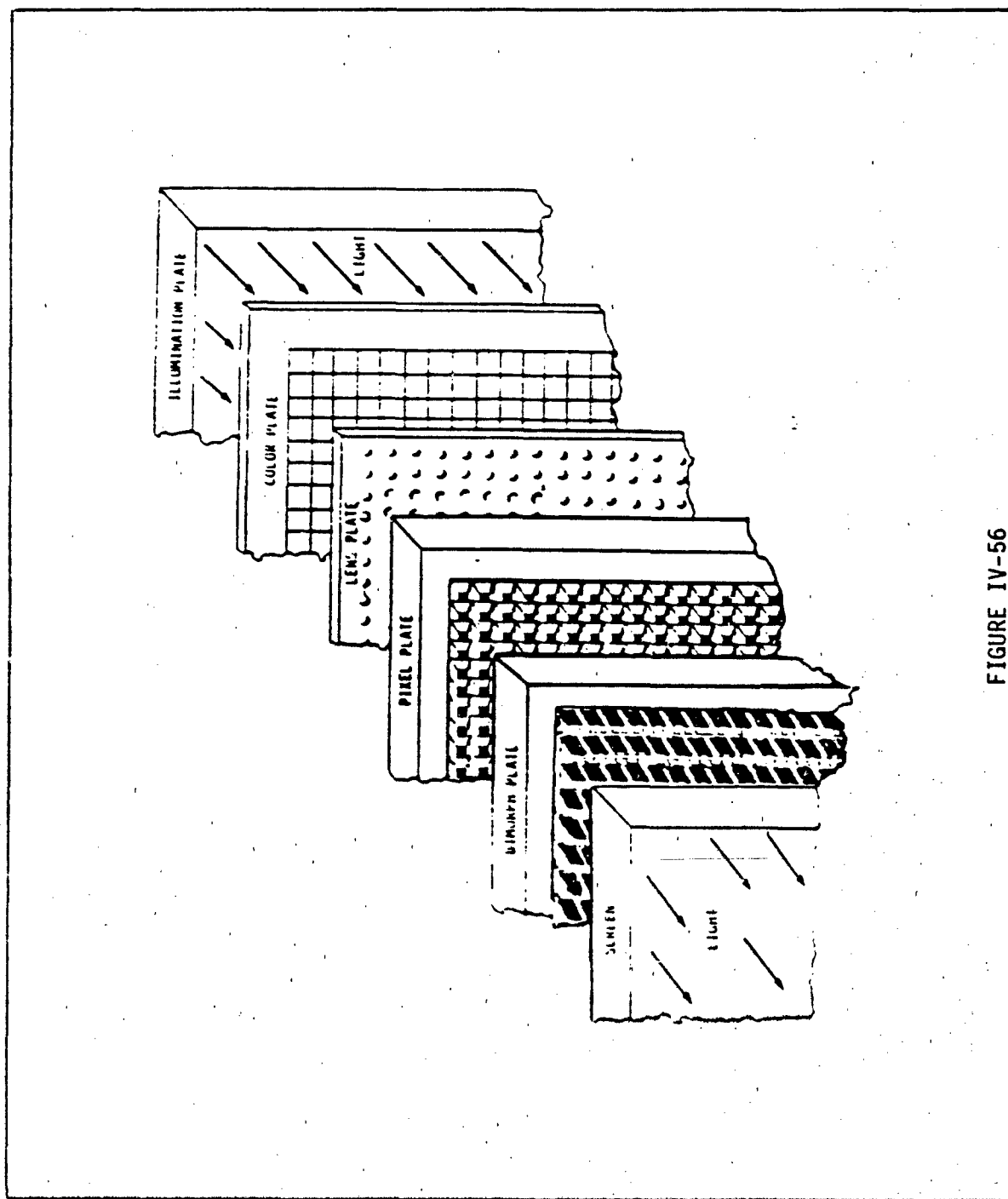


FIGURE IV-56

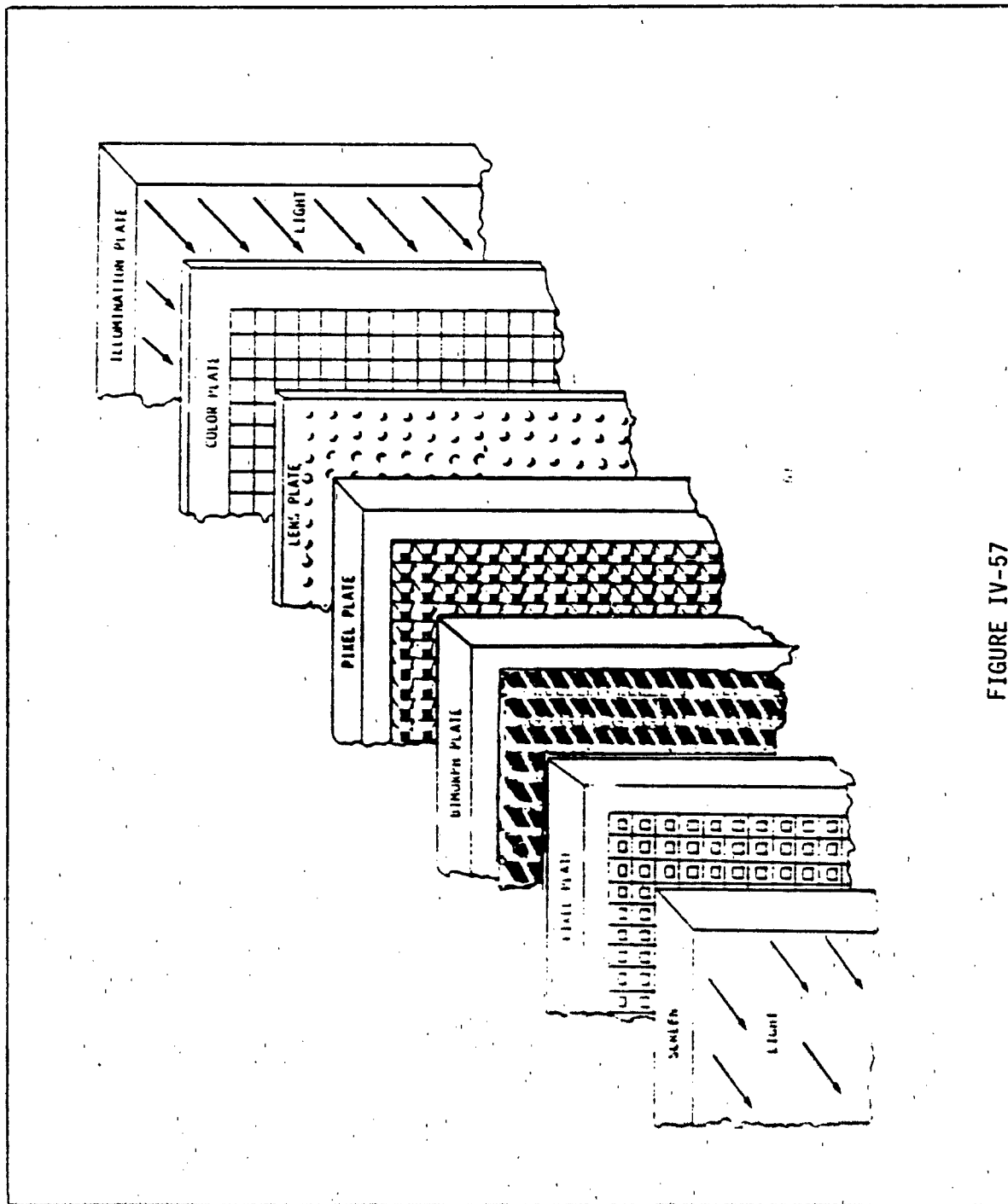


FIGURE IV-57

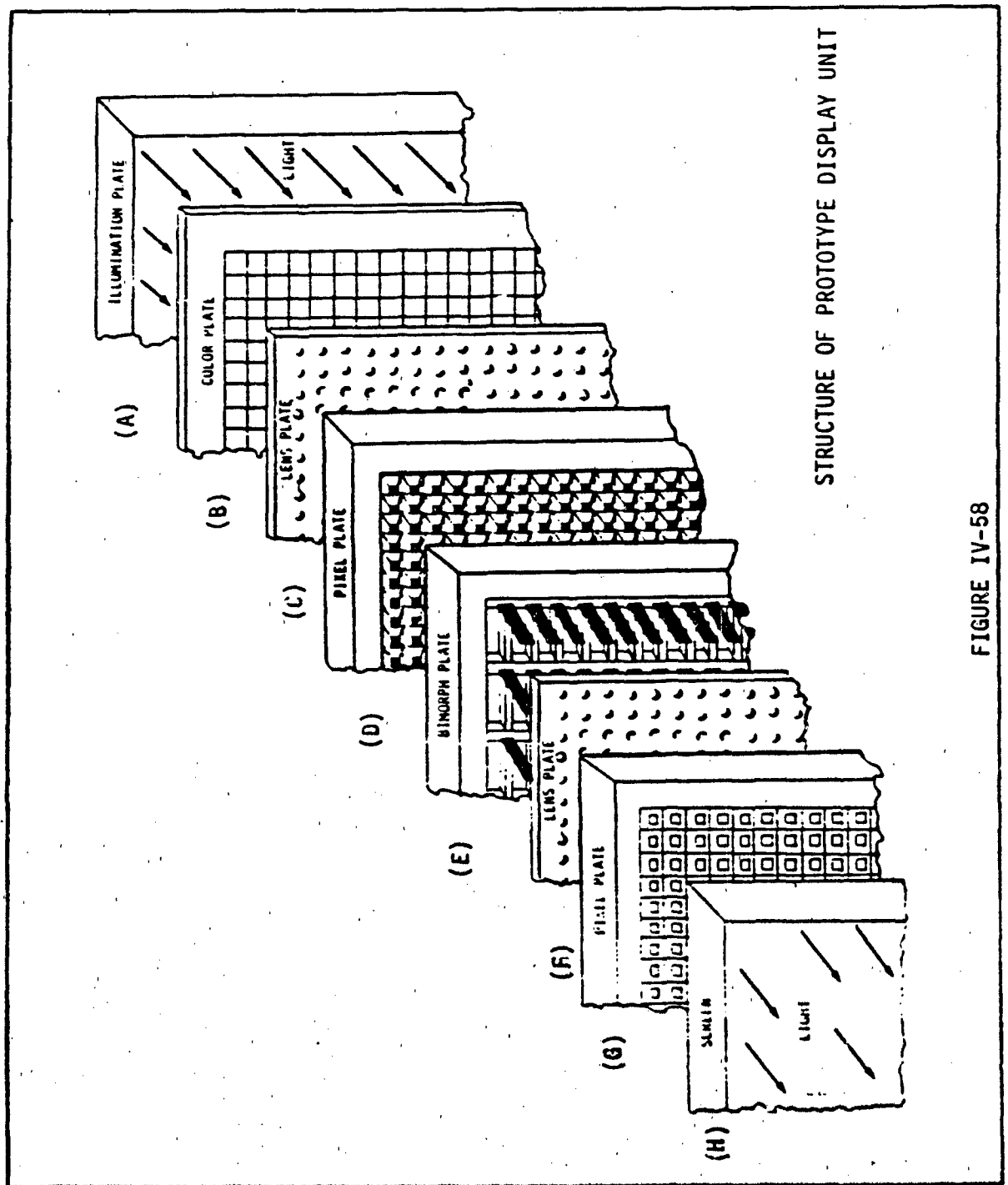
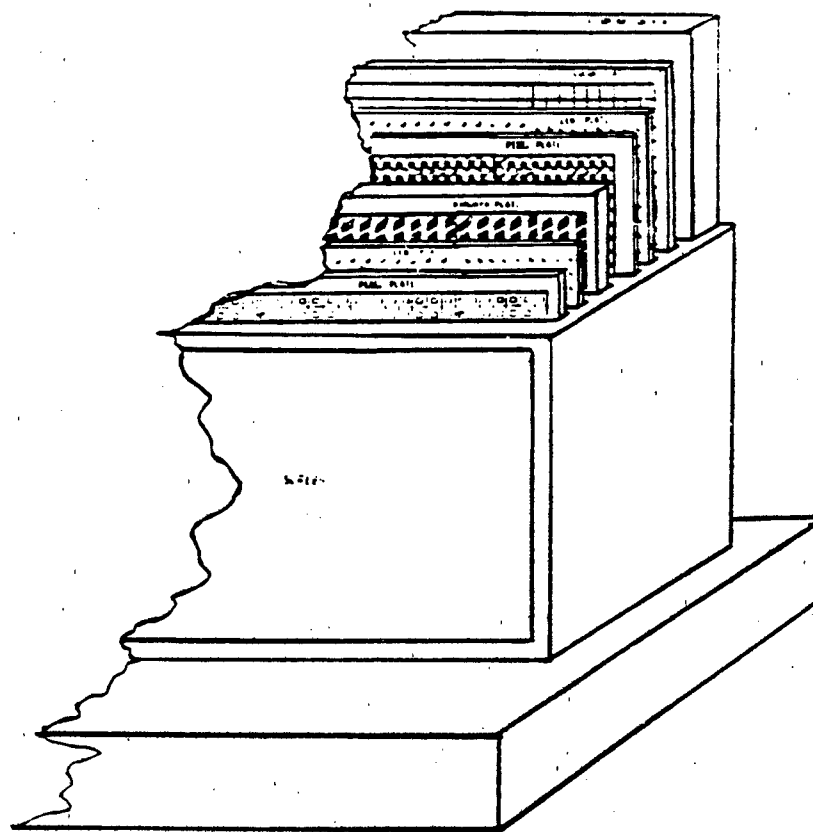


FIGURE IV-58



FLAT PANEL DISPLAY  
TEST CONFIGURATION

FIGURE IV-59

G	R	G	R
R	B	R	B
G	R	G	R
R	B	R	B

G	W	G	W
R	B	R	B
G	W	G	W
R	B	R	B

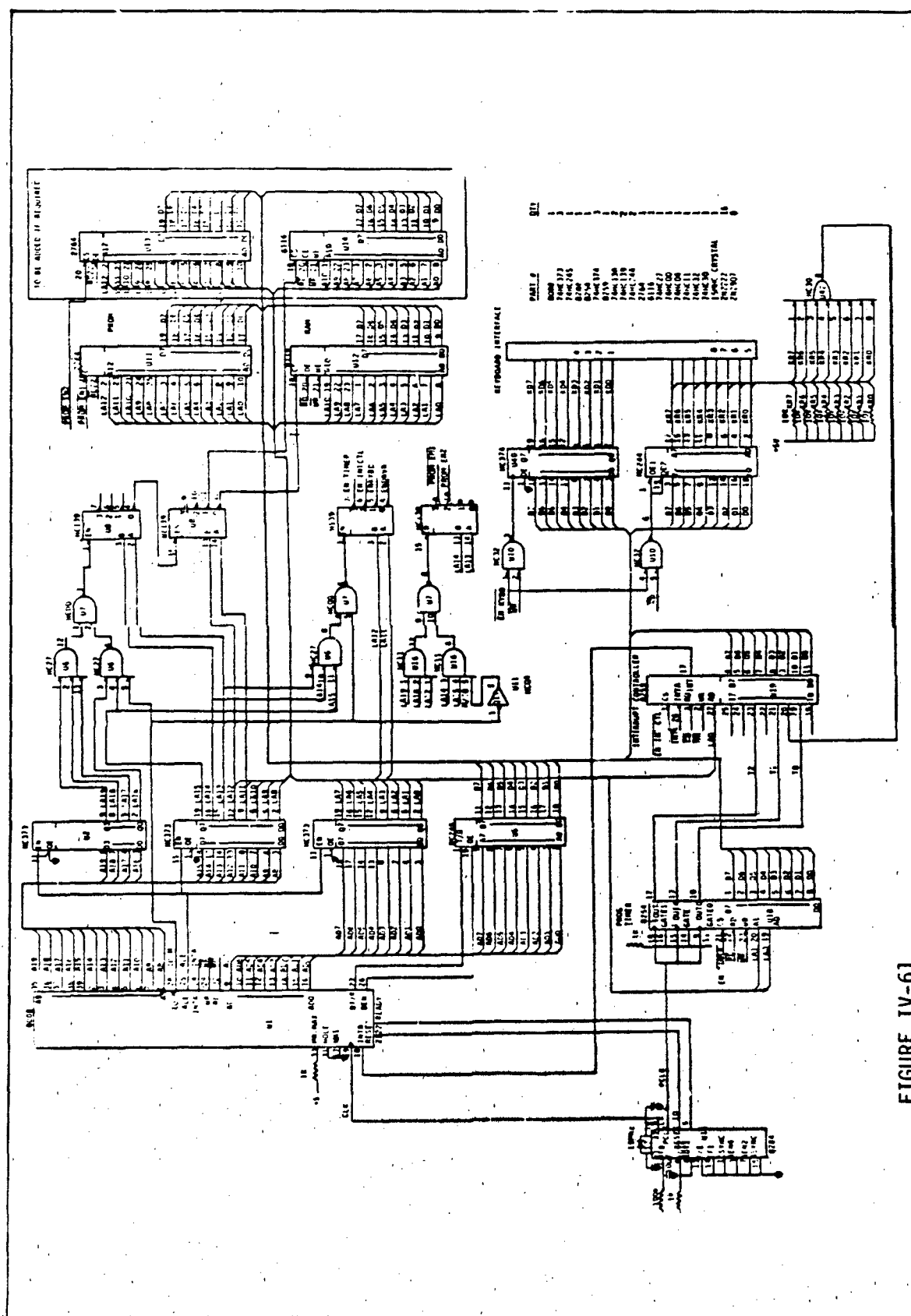
G	G	G	G
R	R	R	R
G	G	G	G
R	R	R	R

Experimental Color Patterns For Flat Screen Display

G	R	G	R	G	R	G	R
R	B	R	B	R	B	R	B
G	R	G	R	G	R	G	R
R	B	R	B	R	B	R	B

Conventional TV Color Dot Pattern

FIGURE IV-60



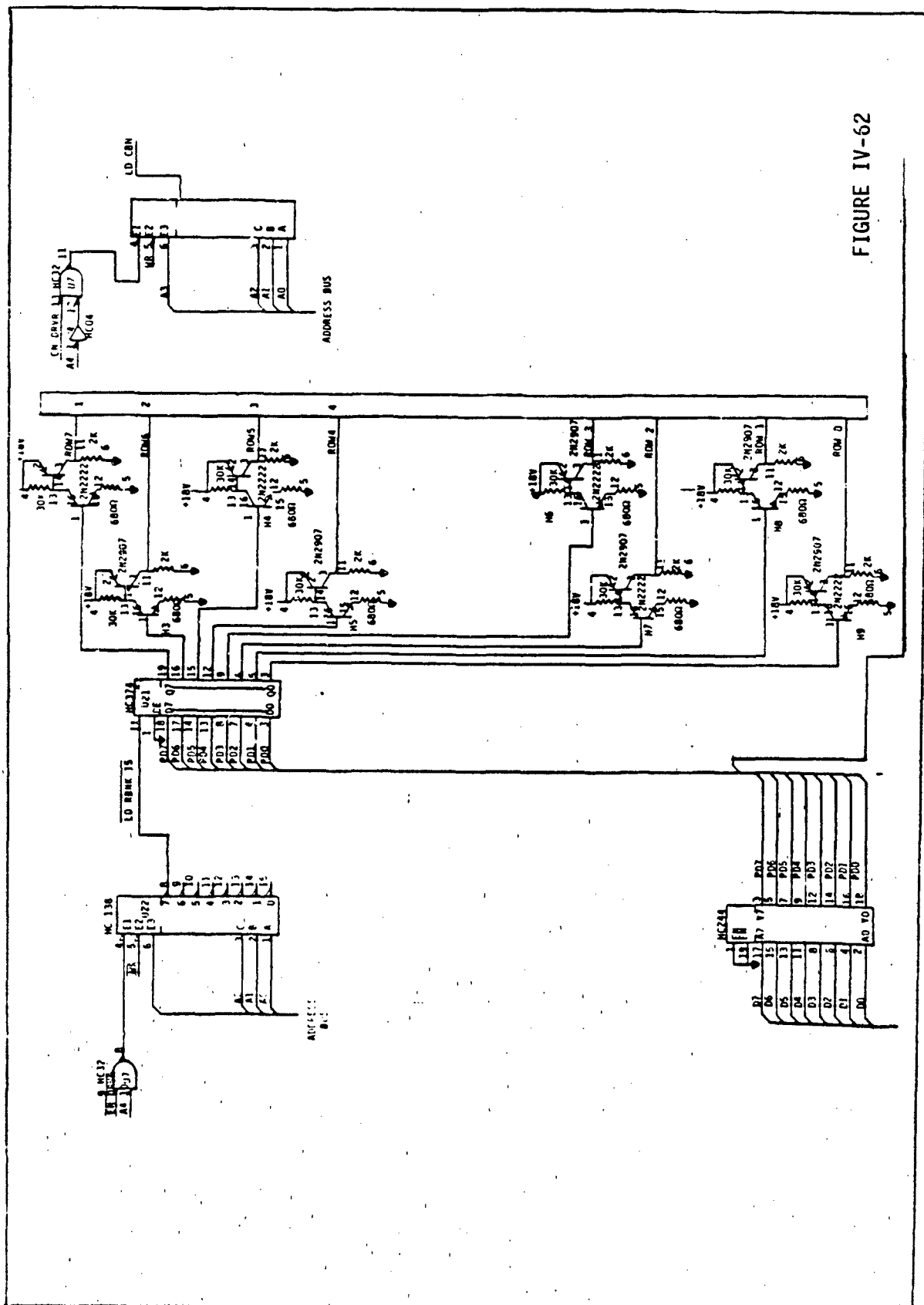


FIGURE IV-62

## 5. PROTOTYPE FABRICATION AND TEST PROGRAM

The prototype display device was designed so that the performance of different configurations can easily be investigated.

Devices based on mechanical modulation techniques are unique in that the illumination element, the image generating element, the element creating the chromatic display can be physically separated and the performance of each investigated independently. Fig. 50 shows the design that was utilized in the prototype display unit. The elements of this display unit consist of:

- An Illumination Plate
- Color Plate
- Lens Plate
- Pixel Modulation Plate
- Plate Containing Bimorph elements
- Optional Light Cone Plate element
- Optional Lens Plate
- Viewing Screen

as shown in Figs. 51 - 59.

During the final months of the program two prototype display units were constructed. Tests are being conducted and planned with 4 x 4, 8 x 8 and 20 x 20 element displays.

The mechanical modulation technique allows a great versatility in the investigation of combinations to produce the optimum color spectrum. As previously indicated, conventional TV systems rely on a basic color triad with the rectangular configuration, different combinations of reds, greens, blues and white can be investigated to achieve the optimum color combinations.

In the early tests, inexpensive color filters were utilized to construct the color plates. As will be indicated in the summary and the discussion of plans for the Phase II program, improved optical color filters, will be investigated.

In the studies of the 4 x 4 display units the initial investigations were carried out without a lens plate. The objective was to study a system utilizing black and white display only without introduction of grey-scale capabilities. Each pixel element in this display was approximately 25 mm in length, and a pixel motion of approximately 4 mm was required to alter the optical state from on to off. This configuration would be particularly appropriate for display applications when rapid changes of displayed data are not required.

Figs. 63 to 69 indicate activities undertaken during the final two months of the program to construct the test models and conduct the planned program tests to demonstrate performance.

A grey-scale is easily produced by mechanical modulation of a light beam when the deflection is linear with voltage. Figs. 64A to 64F show the modulation achievable with the simple optical model shown in Fig. 63.

Steps in the fabrication of the prototype test facility are shown in Figs. 65 to 69.

It should be noted that the series of tests not completed under the formal Phase I program will be completed by Applied Energy Sciences prior to the submission of the Phase II proposal.

In the proposal and in the early stages of project development it was anticipated that a maximum voltage level of approximately 20 volts would be employed. This would enable utilization of the low voltage level CMOS technology. However, in order to achieve desired operation at a maximum level of 20 volts, the bimorphs should be operating in the dynamic rather than in the static mode as indicated in Figs. 24 and 25. When a dynamic mode of operation is utilized optimum performance is obtained when a two element optical valve is utilized, Fig. 28.

Two parallel lines of development are being investigated; one in which the system requirements for image display can be satisfied at relatively low frequency. For this application operation can occur well below the resonance frequency of the pixel. It is anticipated that these displays would be applicable for essentially static displays such as display of maps and information. This configuration would be particularly useful for electronic blackboard applications. The second utilizes bimorphs operating in a dynamic mode.

One future objective of the program is to investigate the potential for dynamic display applications such as TV reproduction or as a display unit for VCR's. Applications as a computer monitor can approach either of these two extremes if dynamic computer displays are anticipated as well as static displays of information.

The primary objective of this program is to develop a display capability for the proof and display of maps. This requirement necessitates the use of a basic pixel configuration containing 4 components. With a pixel dimension of 1.0cm x 1.0cm (containing four color elements), a display capability of 300 lines (conventional color computer monitor) would require a flat screen approximately 3 meters wide.

Tests are planned to determine the capability to reproduce the color spectrum with single pixel elements of 0.5cm x 0.5cm. This would require, for 500 lines, a screen width of 2.5 meters. The aspect ratio (height to width would be 2 to 3). A display model is shown Fig. 70 that is being constructed to serve as a test bed for the program activities between the Phase I program and the proposed Phase II program.

GREY - SCALE TEST APPARATUS

FIGURE IV-63A

Bimorph Tests  
on  
Optical Bench

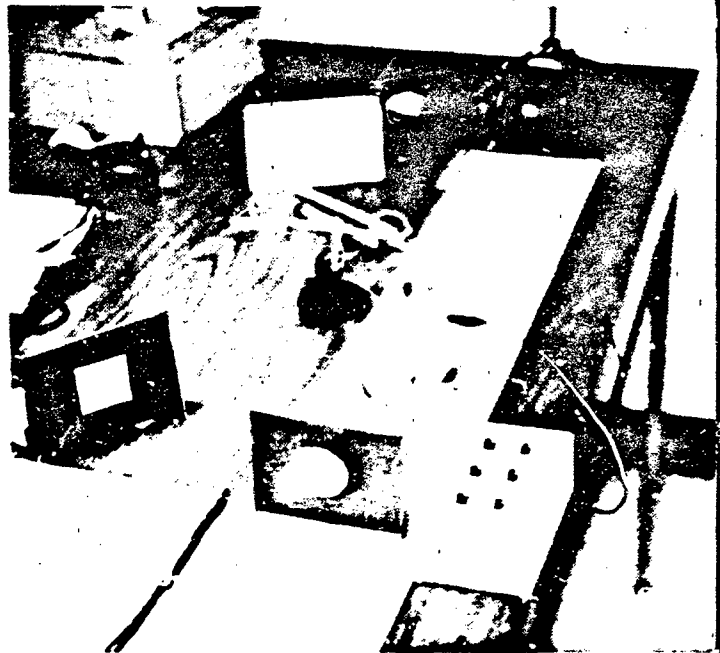
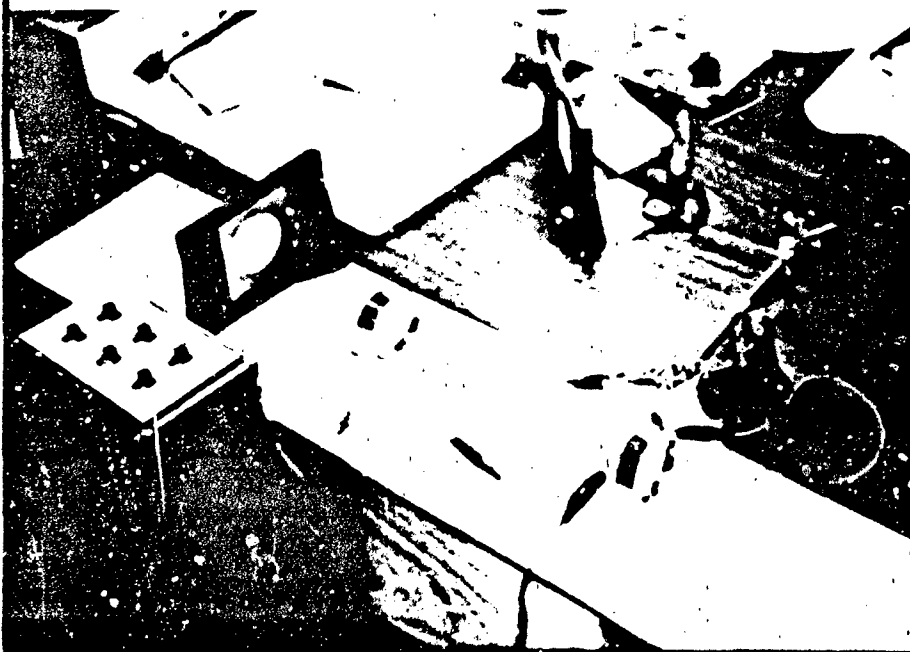


FIGURE IV-63B

Pixel  
Configuration



GREY - SCALE TESTS

FIGURE IV-64A

9 Volts

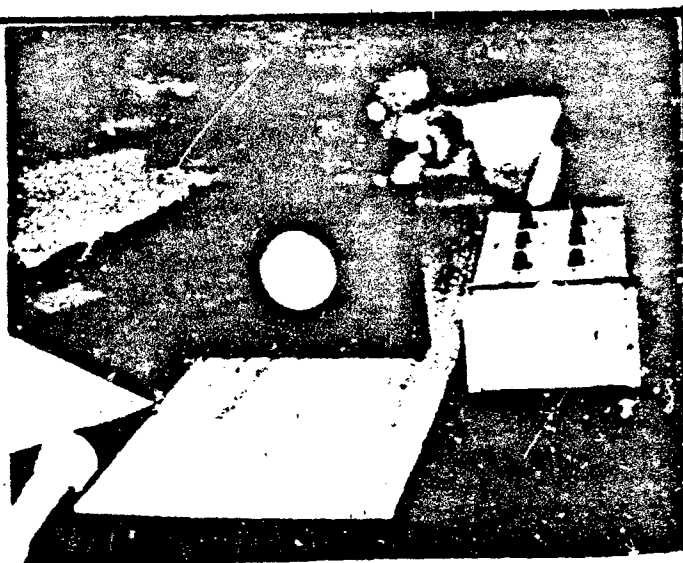


FIGURE IV-64B

18 Volts

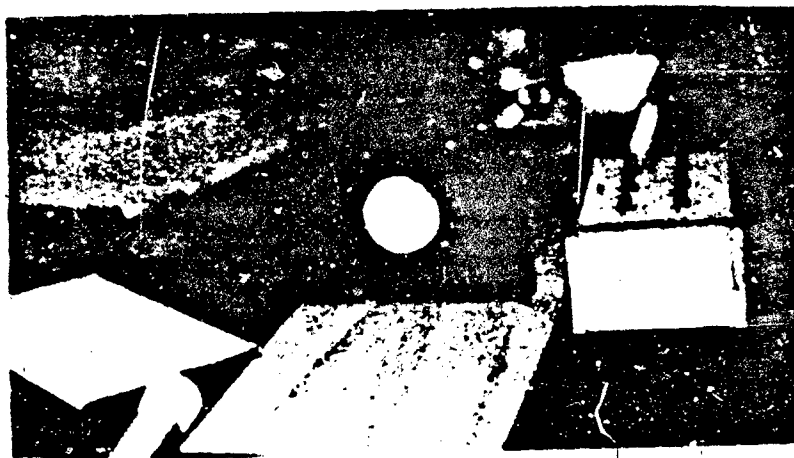
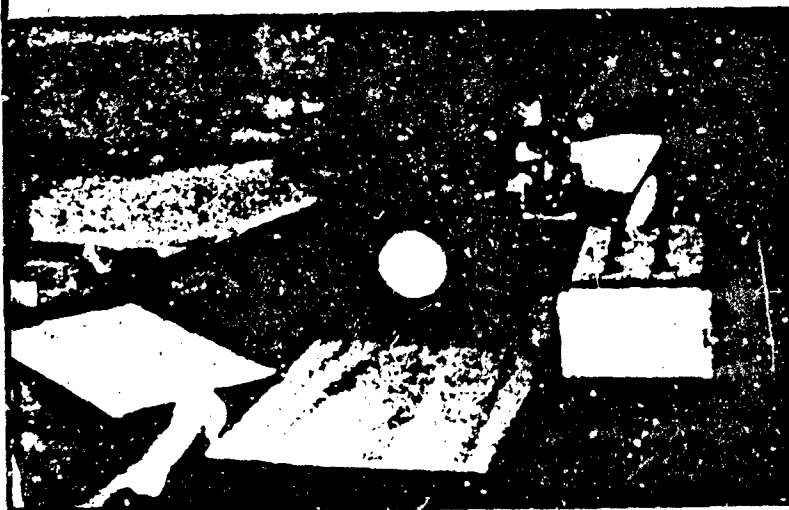


FIGURE IV-64C

27 Volts



GREY - SCALE TESTS CONTD.

FIGURE IV-64D

36 Volts

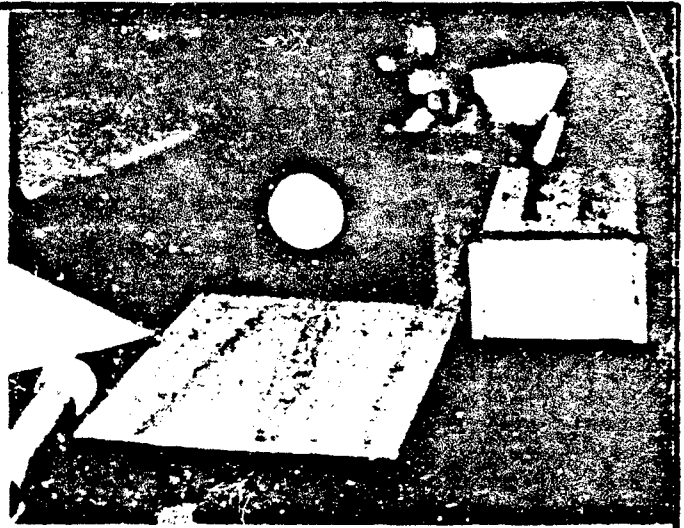


FIGURE IV-64E

45 Volts

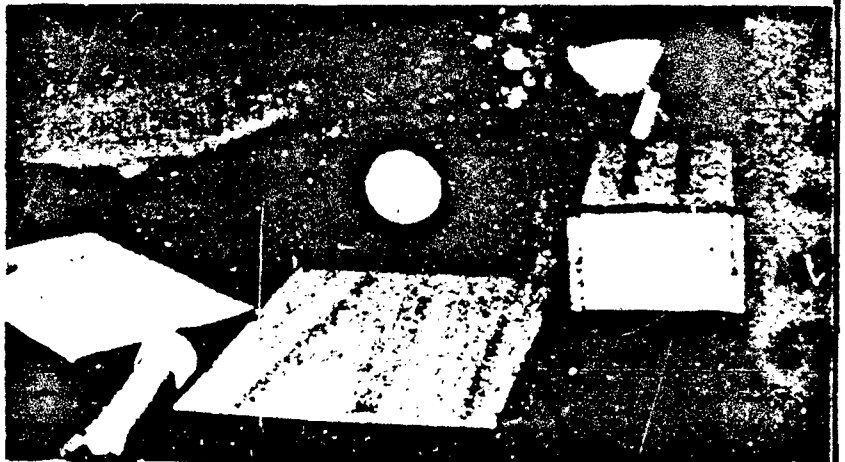


FIGURE IV-64F

54 Volts

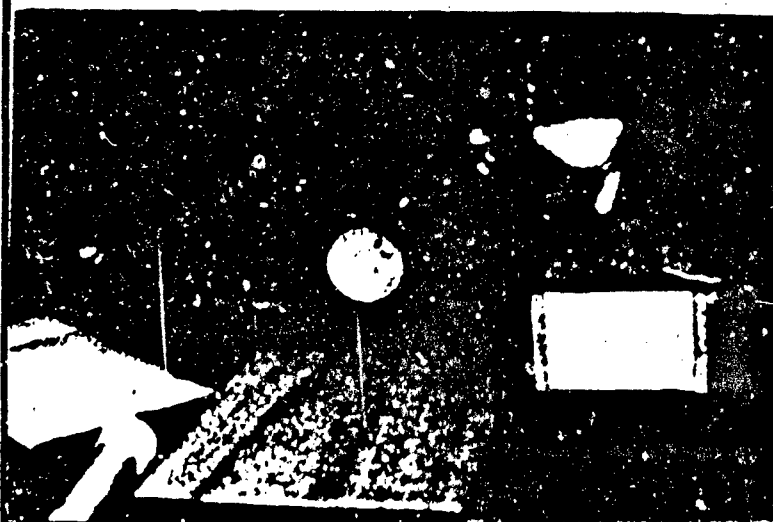




FIGURE IV-65A

Construction of Elements  
for  
Modulation Plate

FIGURE IV-65B

Construction of  
Modulation Plate

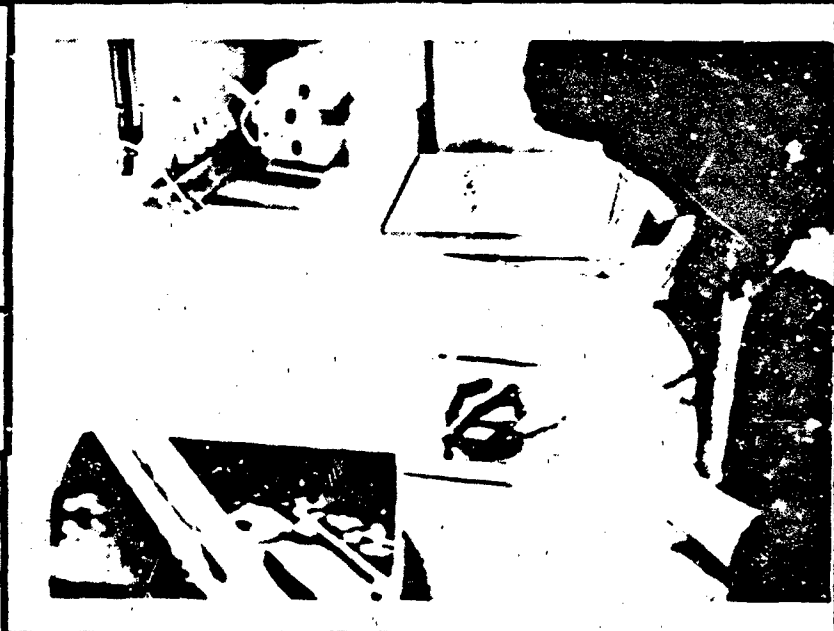


FIGURE IV-65C

Installation  
of  
Modulation Plate  
in Display Unit

FABRICATION OF OPTICAL PLATE

FIGURE IV-66A

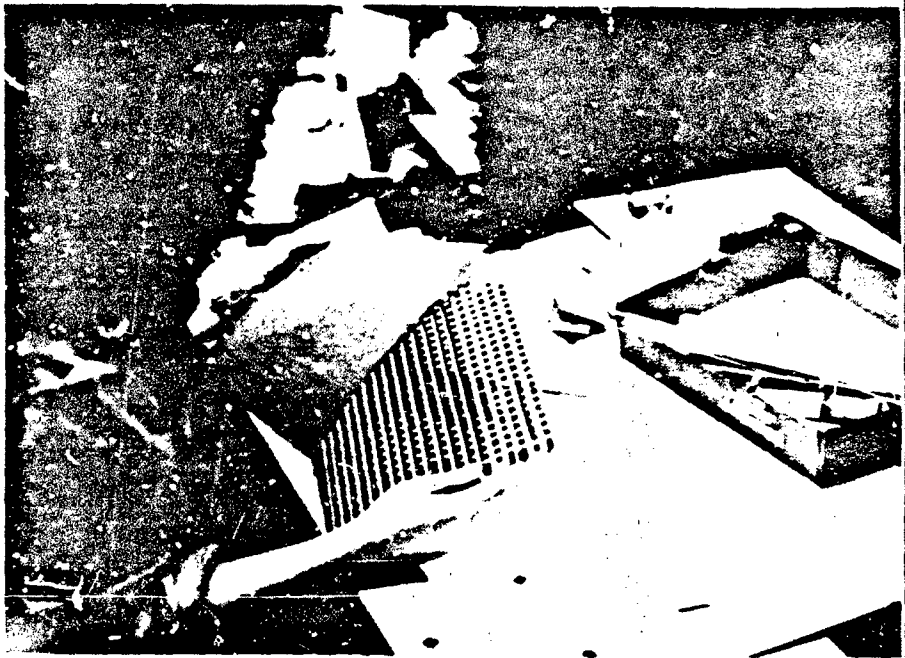


FIGURE IV-66B

FIGURE IV-67A

Installation of  
Test Modulation Plate

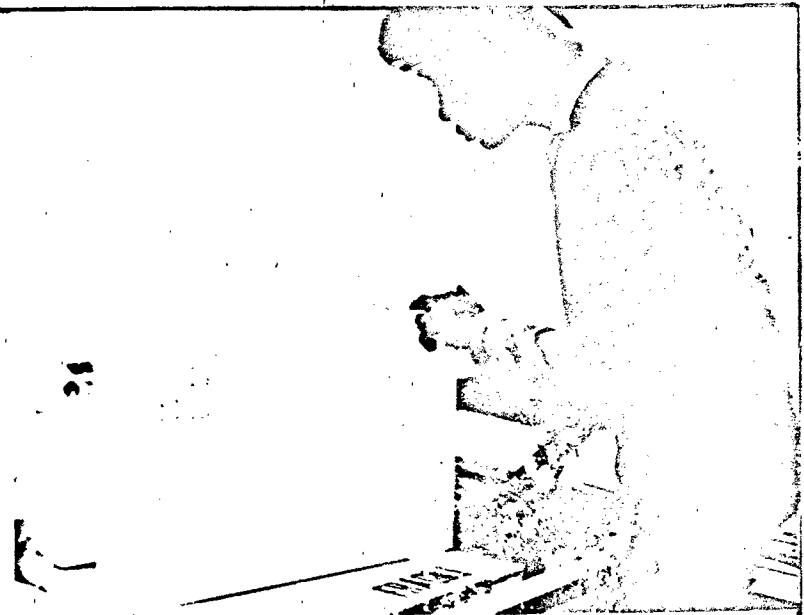


FIGURE IV-67B

Fabrication of  
Illumination Panel

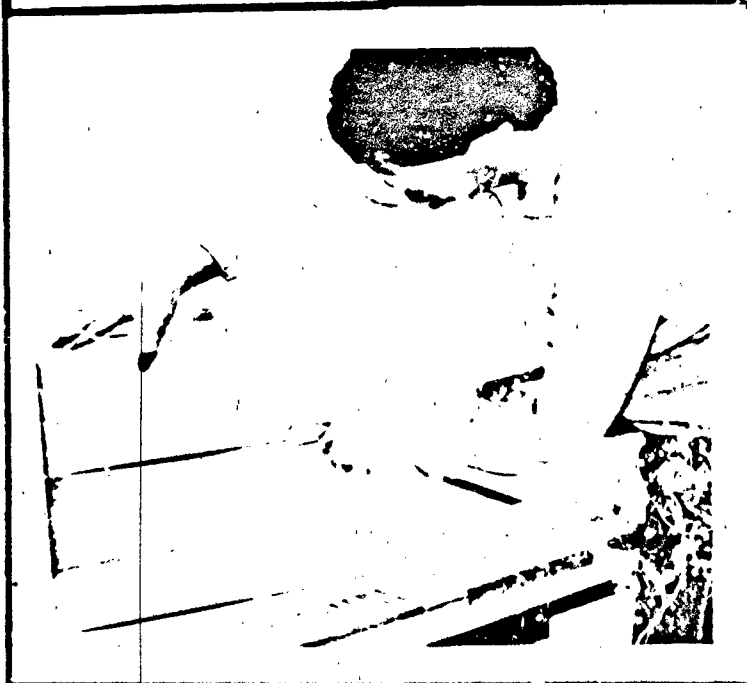


FIGURE IV-67C

Fabrication of  
Illumination Panel



FABRICATION OF COLOR PLATE

FIGURE IV-68A



Construction of Color  
Plate

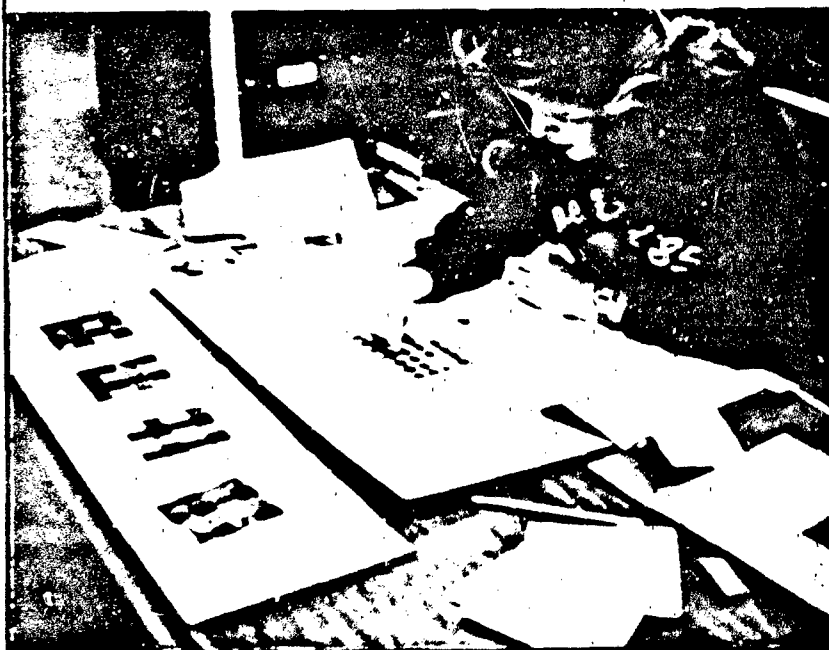


FIGURE IV-68B

Color Pixel  
Configuration

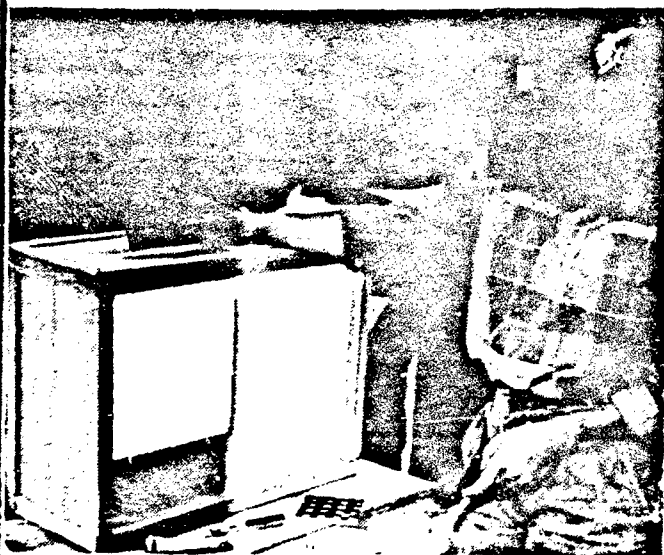


FIGURE IV-68C

Test Of Optical Plate



FIGURE IV-68D



FIGURE IV-68E

Fabrication Of Color Plate

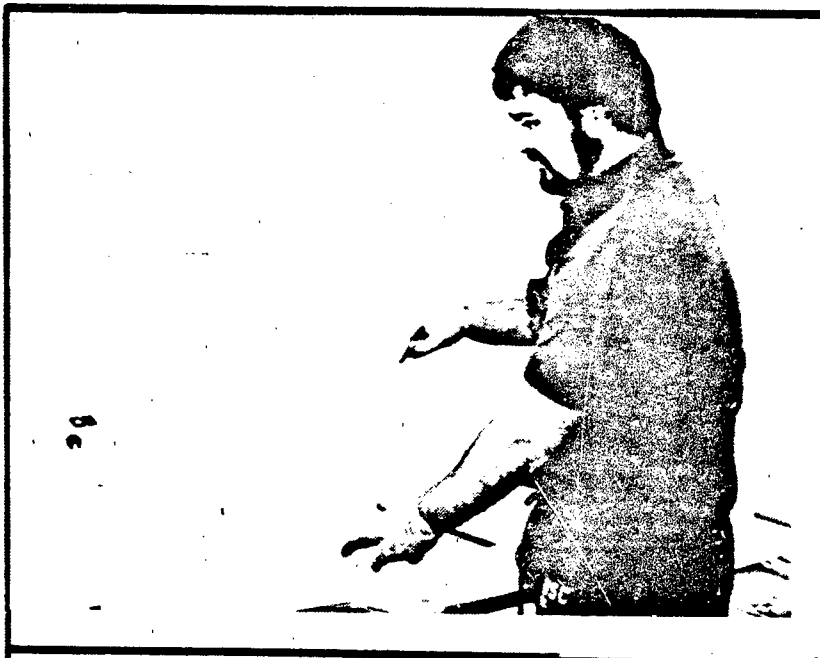


FIGURE IV-69A

Test of  
Illumination Panel

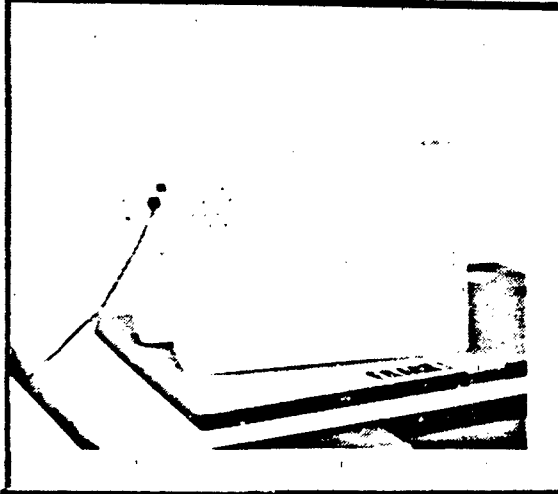


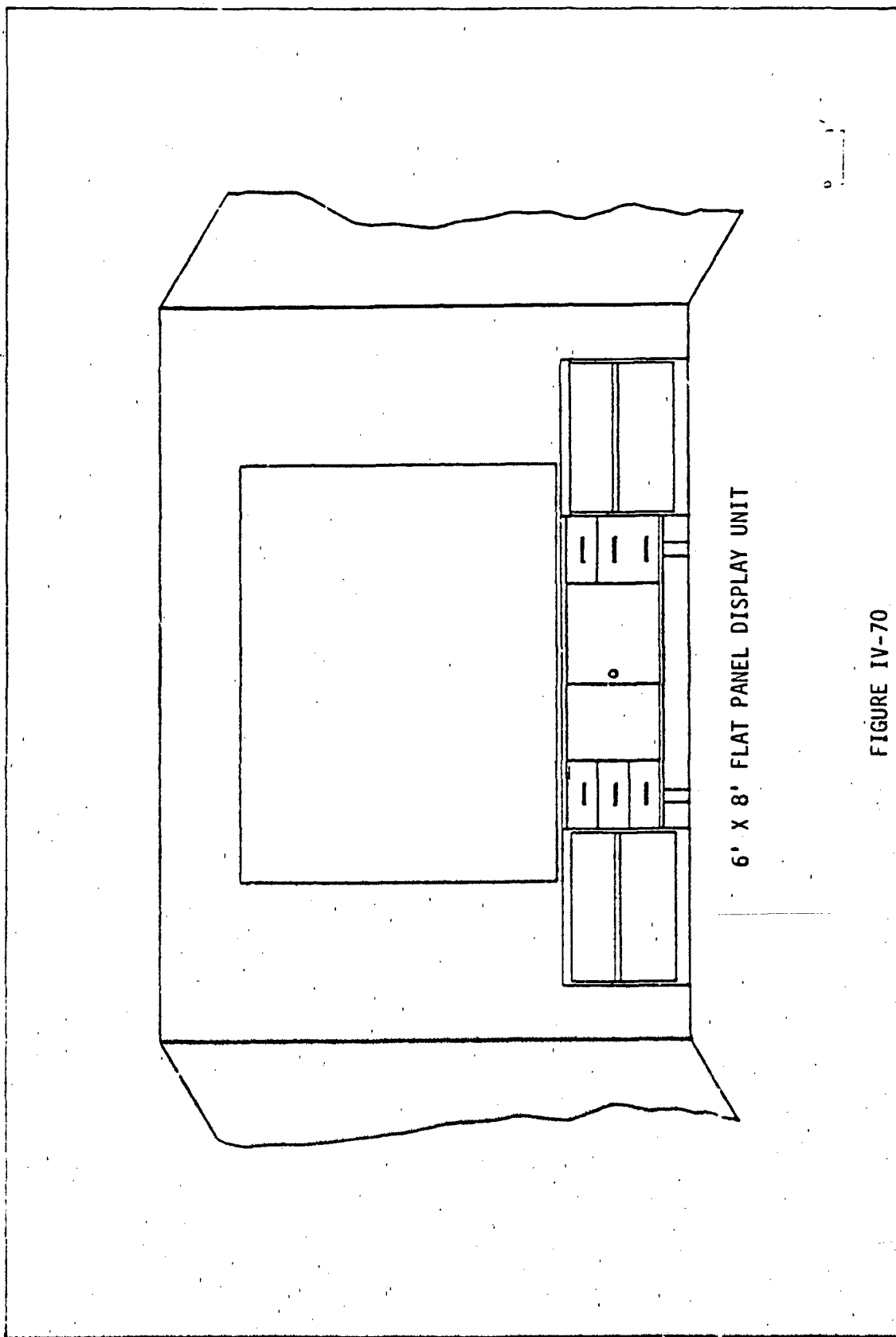
FIGURE IV-69B

Modulation Plate

FIGURE IV-69C

Viewing Screen





## 6. CONCLUSIONS AND RECOMMENDATIONS

In this program, a "new" approach to very large screen display technology is suggested, based on the unique piezoelectric properties of stretched polyvinylidene fluoride films. The objective of this Phase I program, to demonstrate that individual picture elements can be developed, yielding the necessary grey-scale range, to form the basis for large screen display and that these elements can also easily be modified to incorporate full-color display was achieved.

In particular, it is shown that the U.S. Army Engineering Topographic Laboratory requirement for a large-scale, high resolution software display to proof and display maps and charts can be satisfied using this approach.

The tests with piezoelectric bimorph elements have shown that the deflections over the voltage ranges 20-90 volts are adequate for a number of display applications. The linear variation with voltages enables grey-scales to be generated. Colors can easily be mixed to generate full color range. Elements of the display are easily fabricated. The baffle plates, lens plates, etc., are easily formed by compression molding techniques. The Pennwalt Corporation has developed techniques for metallizing films, Fig. 71. Metallization patterns are simple for the bimorph modulation plates, Figs. 72-73.

The prototype display device was designed so that the performance of different configurations can easily be investigated.

Devices based on mechanical modulation techniques are unique in that the illumination element, the image generating element, the element creating the chromatic display can be physically separated and the performance of each investigated independently. The elements of the display unit consist of:

- ° A fluorescent illumination plate (A)
- ° Color plate (B)
- ° Lens plate (C)
- ° Pixel modulation plate (D)
- ° Plate containing bimorph elements (E)
- ° Optional light cone plate element (F)
- ° Optional lens plate (G)
- ° Viewing screen (H)

Two experimental display units were constructed and tests are being initiated.

The mechanical modulation technique allows a great versatility in the investigation of combinations to produce the optimum color spectrum. Conventional TV systems rely on a basic color triad. With the rectangular configuration, different combinations of reds, greens, blues and white can be investigated.

In the early studies of the 4 X 4 display units the initial investigations

were carried out without a lens plate. The objective was to study a system utilizing black and white display only without introduction of grey-scale capabilities. Each pixel element in this display was approximately 2.5cm long and 0.50cm in width. A pixel motion of approximately 4 mm was required to alter the optical state from on to off.

This configuration is the simplest and most inexpensive to construct, but may nevertheless possess major commercial potential since it could form the basis of a simple black and white large flat panel computer display. As indicated in Exhibits A-E, there is interest in such a development.

The research activities conducted during the six month period documented in this Report, although successful, indicated that additional development work would be required before a production-type display unit could be developed. Development studies that would be required include:

1. Formulation of standardized test procedures when poled films are received to ensure:
  - a. uniformity of poling, i.e., achievement of required film characteristics;
  - b. Integrity of vapor deposition of electrodes.
2. Development of electrode bonding techniques to ensure integrity of bonds and achievement of required reliability and lifetime.
3. Optimization of performance characteristics for specific applications including:
  - a. film thickness;
  - b. film length and width to ensure stability and accuracy of alignment in optical valve plate;
  - c. operational voltages;
  - d. operational mode, static or dynamic;
  - e. adhesive layer thickness, etc.;
  - f. two or three electrode configuration,
4. Selection of pixel configuration for optimization of color reproduction.
5. Detailed designs for matrix address system, including:
  - a. Operational characteristic, i.e., repetition rates, pulse, width, pulse amplitude, etc.;
  - b. memory and refresh rate requirements;
  - c. operational configuration when very high scan rates are required.

6. Procedures for fabricating and producing complete columns or rows of bimorph elements comprising the optical modulation plate.
7. Techniques for fabrication of the modulation plates assuring accuracy of alignment of elements of the plate.
8. Design of baffle plates, grids of the modulation plates and optical plates for injection molding or similar molding operations.

Once the basic information is obtained in the planned series of development tests that would be designed to satisfy the Army requirements, the required number of display units would be designed, fabricated, tested and delivered during the Phase II program.

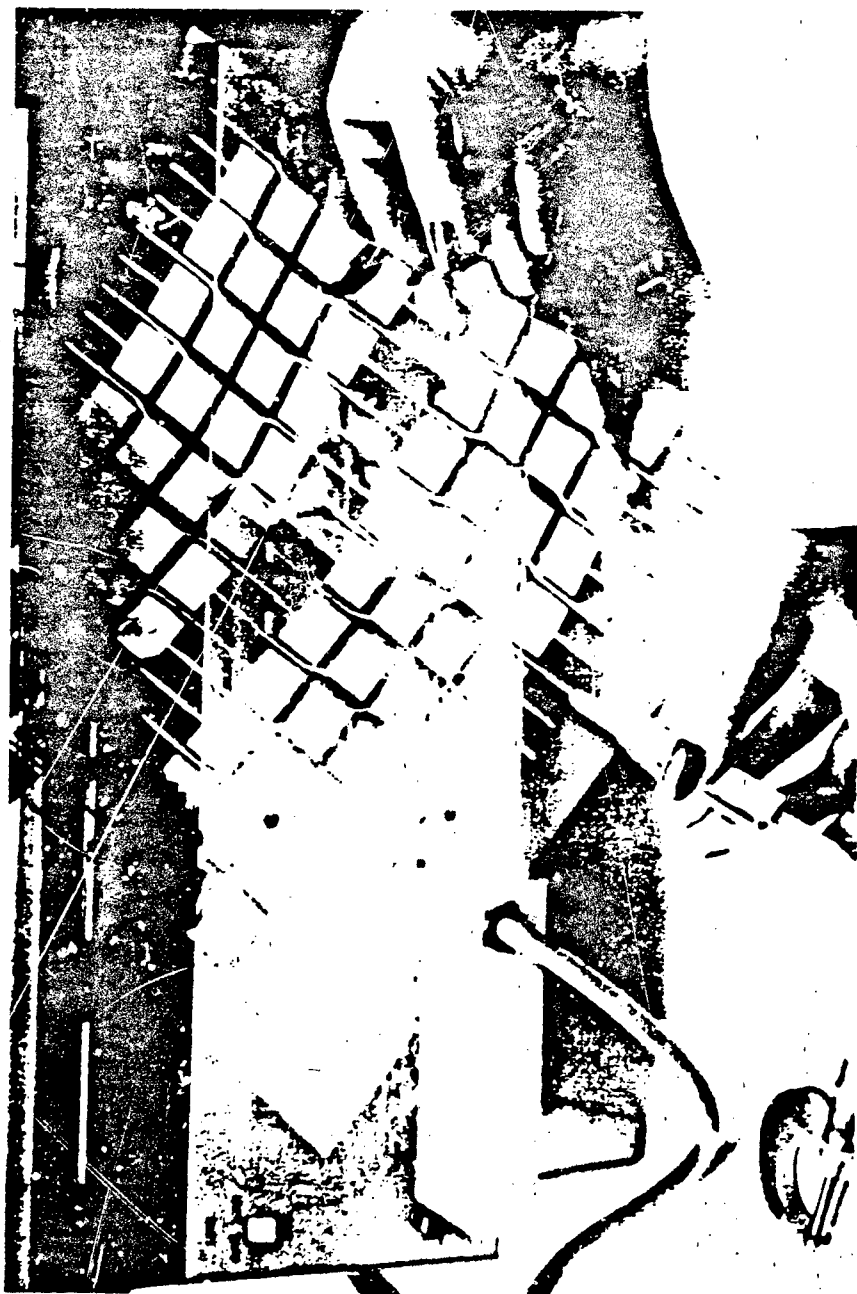
The following Phase II activities are planned:

1. Review of bimorph studies to identify and develop:
  - (a) Appropriate fabrication techniques for large pixel numbers;
  - (b) Appropriate fabrication techniques for color plates and lens plates to achieve described color reproduction and grey-scale reproduction capability;
  - (c) Light panels that can be assembled in sections to provide ample illumination;
  - (d) Required matrix address system capability (use of high voltage drivers).

As an in-kind contribution to the Phase I effort, upon completion of the formal contract period authorized for Phase I, the basic studies will be continued by AES, Inc. The objective is to obtain additional information for planning of the Phase II contract development activity. These studies will include:

1. Bimorph tests to study long term performance, integrity of simple electrode attachment procedures, performance decay, etc.
2. Studies of color simulation to identify appropriate optical quality color filters and techniques to achieve color reproduction quality to equal that of current color display systems.
3. Fabrication of additional matrix address electronics to vary drive voltages over ranges to achieve improved grey-scale performance and more precise control with stiffer elements.
4. Design and fabrication of clear plastic lens sheets using injection molding of clear acrylics or other suitable technique.
5. Study of fabrication of row and column metallized electrode configurations and assembly techniques, etc.

This will enable a core staff to be retained to provide a smooth transition to the Phase II activity summarized above.



Shaped to fit. Kynar piezo film can be shaped to form just about any desirable configuration, while retaining its full piezoelectric and pyroelectric properties. The film is pliant and lightweight.

FIGURE IV-71

Metallization Pattern for Two - Electrode Bimorph

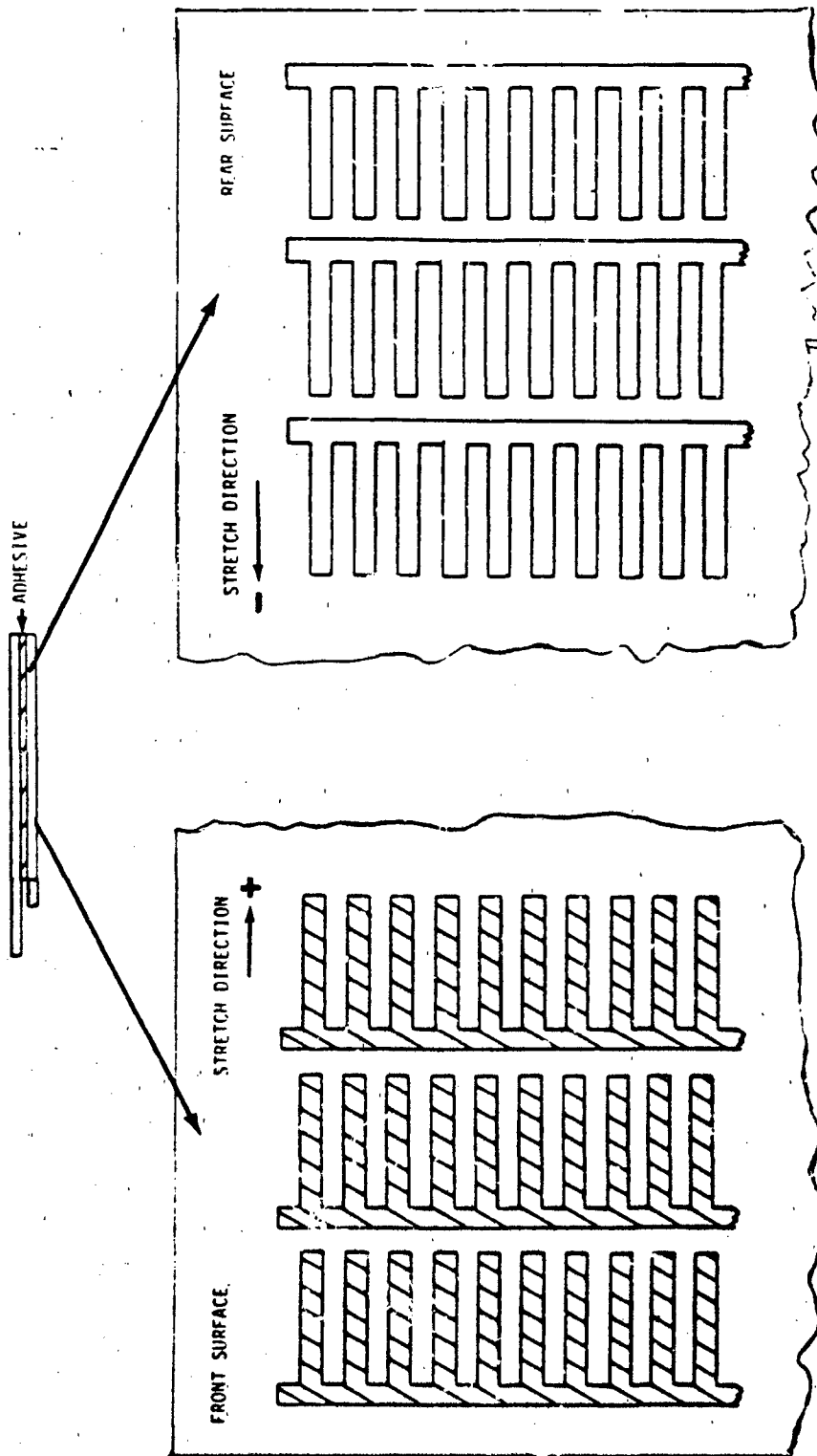


FIGURE IV-72A

Metallization Pattern for Two - Electrode Bimorph

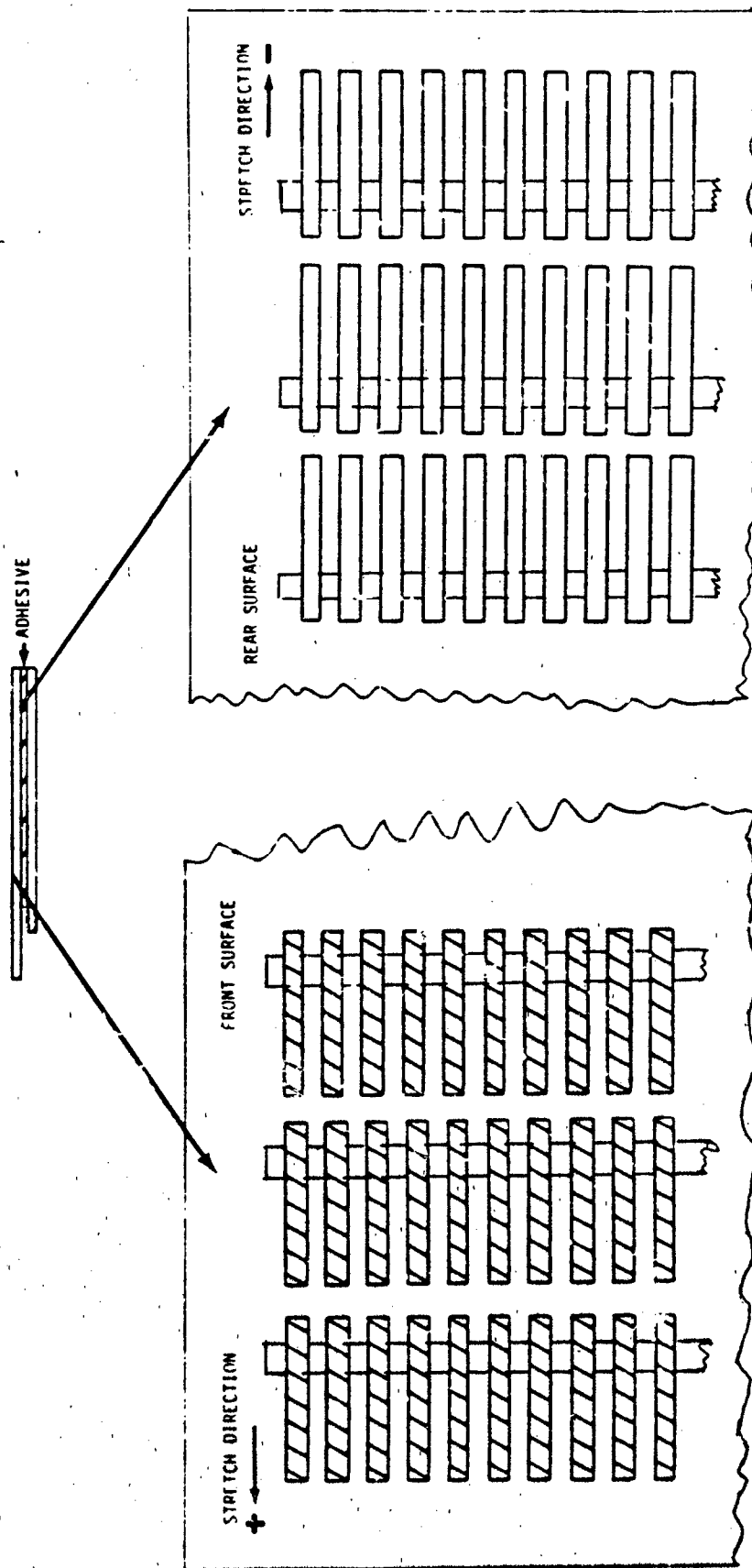


FIGURE IV-72B

Metallization Pattern for Three - Electrode Bimorph

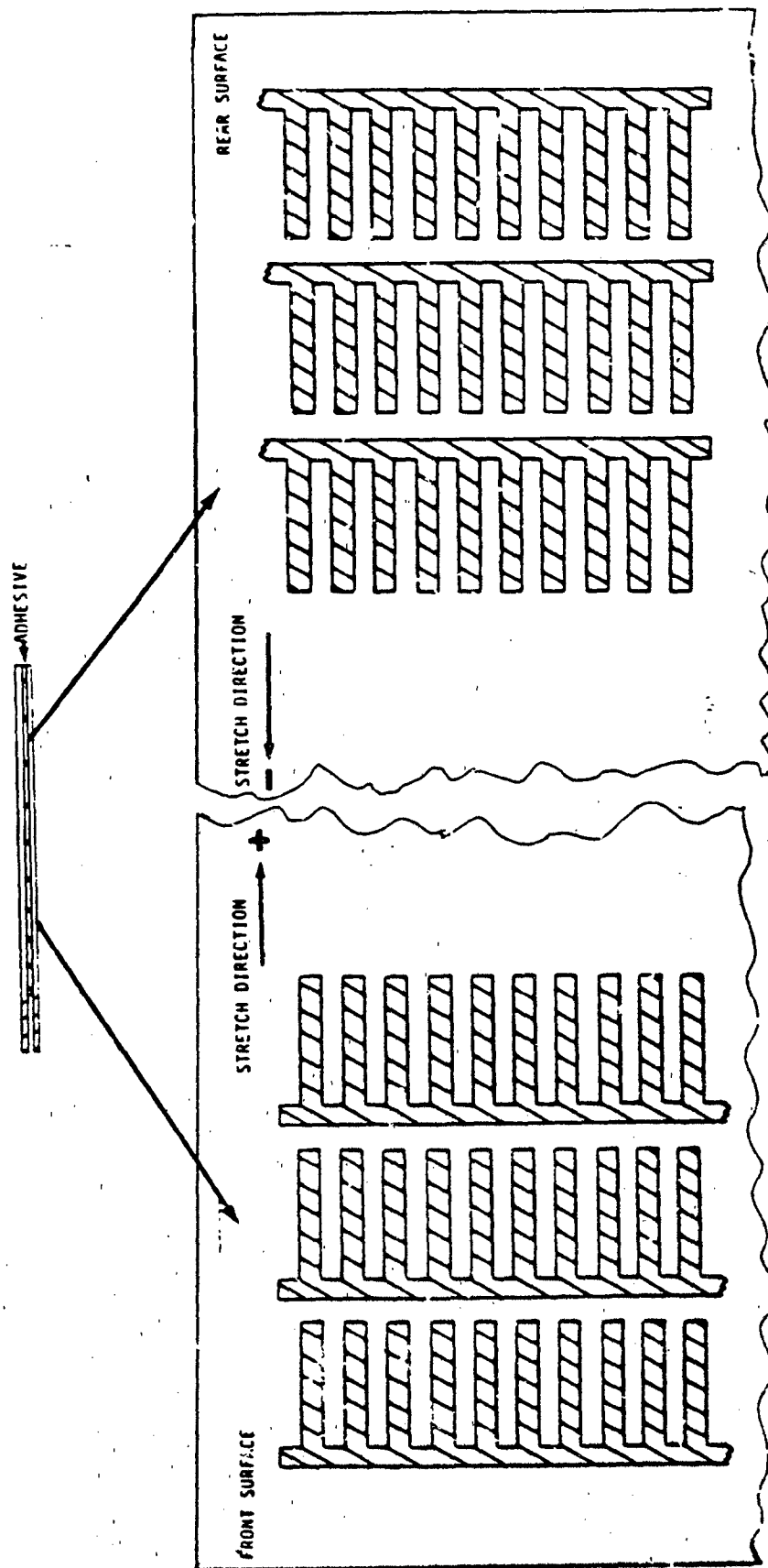


FIGURE IV-73A

# Metallization Pattern for Three - Electrode Bimorph

ADHESIVE

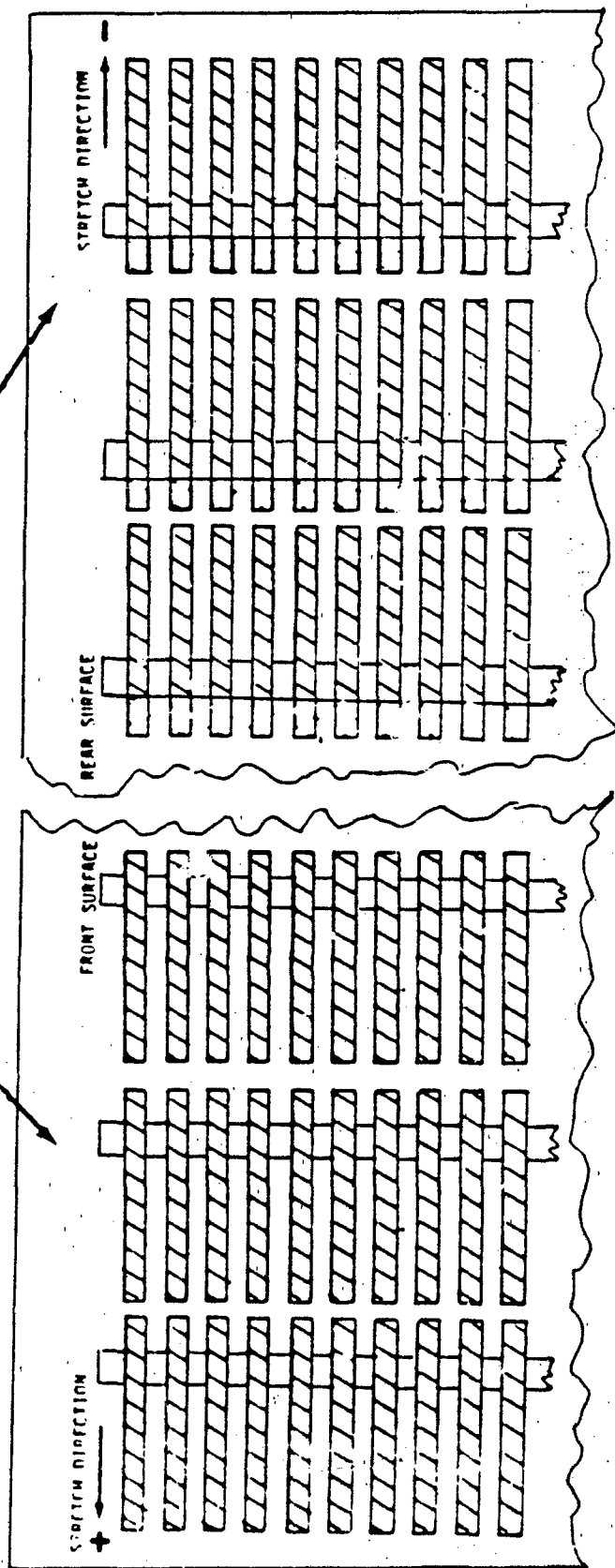


FIGURE IV-73B

EXHIBIT IV-A

UNION VENTURE CORPORATION

SPECIAL INVESTMENT GROUP OF THE UNION BANK OF CALIFORNIA  
447 SOUTH FLORENCE STREET, LOS ANGELES, CALIFORNIA 90013  
TELEPHONE 213-539-6781

January 31, 1985

Mr. Joseph G. Logan  
Applied Energy Sciences, Inc.  
3652 Olympiad Drive  
Los Angeles, California 90043

Dear Mr. Logan:

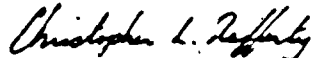
I read with great interest about the research which you or your company is conducting under an SBIR award. Union Venture Corporation is highly interested in new technologies which have potential commercial applications. If you possess commercially viable technologies (whether or not developed under the SBIR program), and you are in the market for venture capital, we would welcome the opportunity to discuss making an investment with you.

By way of background, Union Venture Corporation is the venture capital subsidiary of Union Bank. We specialize in financing early-stage technology based companies. Some of our past winners include Andahl, Storage Technology, Four Phase Systems, Data 100, Network Systems, Integrated Device Technology, Silver-Lisco and Gradco Systems.

Approximately half of our investments involve companies the business of which is at the conceptual or prototype level, with no product sales. The balance consists of later stage companies. We currently have a limit of \$2 million per investment, however we are investing in early-stage companies at the rate of \$500,000 to \$750,000 per deal, reserving additional buying power either for adversity or growth opportunities.

To better acquaint you with our operations and objectives, I enclose some supplementary materials. I hope to hear from you sometime in the near future.

Sincerely yours,



Christopher L. Rafferty  
Vice President

vl  
Enclosures

EXHIBIT IV-B

# UNITED

INVESTMENT GROUPS INC

504 North Second Street

Portland, Iowa 52556

(515) 472-8200

October 10, 1984

Joseph G. Logan  
Applied Energy Sciences, Inc.  
3652 Olympic Drive  
Los Angeles, CA 90043

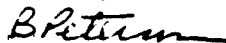
Dear Mr. Logan:

Our firm provides venture capital for promising research and development projects. We are currently forming a \$7.5 million publicly registered R&D pool which will, in part, be dedicated to funding Post Phase I SEIR programs.

I have read an abstract of your SEIR phase I project and find the concept very interesting. If a need exists for follow-up funding for your project I invite you to forward your project proposal and business plan for our review.

I have enclosed information on United Investment Groups for your reference. Thank you for your attention.

Sincerely,



Bryan Peterson  
Vice President  
Project Development

BP:mdo

Enclosure

10-5  
RESEARCH & DEVELOPMENT

EXHIBIT IV-C

**Raychem**

Raychem Corporation

August 17, 1984

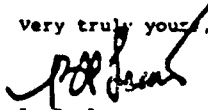
Joseph G. Logan  
3652 Olympian Drive  
Los Angeles, CA 90043

Dear Mr. Logan:

We have read with interest the abstract of your project in the Small Business Innovation Research Program Phase I - Awards publication, "New Large Scale, High Resolution Multi-Color Software Display Concept." Your work may be relevant to Raychem's interests, so I would like to have additional information about your work and its status.

We will be back in touch with you after reviewing the received information.

Very truly yours,



E. F. Levin  
Business Ventures Department  
Raychem Corporation

BPL:kk

EXHIBIT IV-D



920 First Avenue, P.O. Box C, King of Prussia, Pennsylvania 19406-0001 • (215) 377-6500

July 17, 1984

Dr. Joseph G. Logan  
Applied Energy Sciences, Inc.  
3652 Olympiad Drive  
Los Angeles, California 90043

Dear Dr. Logan:

We have recently learned of your selection for Department of Defense SBIR Phase I research support on a "New, Large Scale, High Resolution Multi-Color Software" and would like to learn more about your project.

Pennwalt, a large company involved in chemicals, health products and equipment, has interest in this area and would consider a Phase III contingent commitment agreement. If you do not already have such an agreement and would like to pursue the possibility of one with Pennwalt, please contact me.

Sincerely,

A handwritten signature in dark ink, appearing to read 'Paul Tubbs'.

Paul Tubbs  
Manager -  
New Technology Assessment

PT:ds

cc: E27  
N16  
N32

EXHIBIT IV-E

June 20, 1984

Joseph C. Logan  
APPLIED ENERGY SCIENCES, INC.  
3650 Olympiad Drive  
Los Angeles, CA 90048

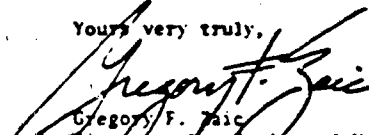
Dear Mr. Logan:

Cambridge is a venture capital firm looking for new products to commercialize. A brochure describing our activities is enclosed. I read with interest the work on large scale, high resolution multi-color software display that you are doing for DOD under a Phase I SBIR grant.

We might be interested in funding the commercial development of your project, if it at least meets two criteria: a strong proprietary position (usually patented) and a working prototype.

If it appears there's a fit here, please contact me.

Yours very truly,

  
Gregory F. Zalc  
Director, New Products & Ventures

GFZ/doc  
Enclosure

It appears that flat panel display devices based on the use of PVDF film elements acting as light modulators or mechanical valves possess similarities in the operational requirements to flat panel display devices based on the electroluminescent technology (EL) and the plasma technology. Both of the technologies require modification of a voltage pulse (amplitude, pulse width, rise time, etc.) to achieve gray scale capability and both require voltage pulses in the 100-200 volt range, rather than the 10-20 volt range employed by liquid crystal display (LCD) devices.

The requirements of the EL technology have led to the development of special high voltage drivers with the capability of generating 16 levels of gray to satisfy the Army requirements,<sup>1</sup> Fig. 74. This technology is immediately adaptable for the operation of mechanical valve display (MVD) devices employing PVDF films. In addition, operation with PVDF films at the higher voltage levels employed to drive EL displays enable the use of small film elements resulting in improved resistance to shock and vibration since greater rigidity results.

The simplest form of the MVD display is a bi-level display (off-on). The bi-level display is also the basic form of the EL and plasma displays. In the development of the MVD system, pixel plates (G, Fig. 58) were designed to act as light guides to ensure complete isolation of neighboring pixel elements. Additional system construction and configuration details are shown in Figs. 75 to 84.

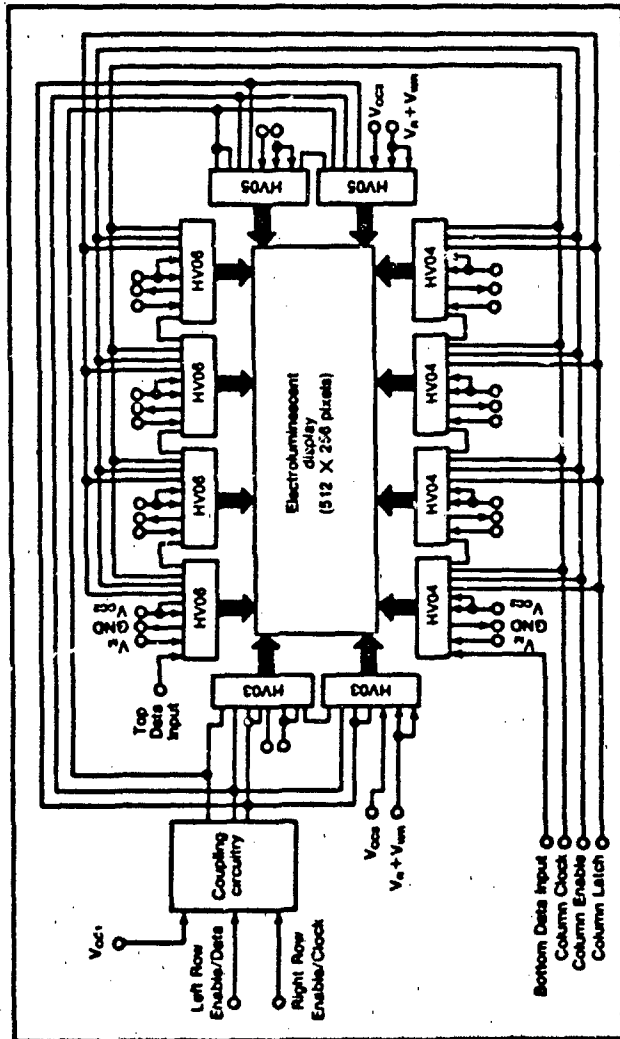
The effectiveness of the pixel plate (G) acting as a light guide to isolate the pixels is indicated in Fig. 85. Although different degrees of closure of the elements of the 4x4 matrix were used, the boundaries between the different pixels are clearly delineated, indicating that the neighboring pixels are not affected.

Since the effects of individual pixels can be completely separated from the effects in adjacent pixels, complete contrast can be attained. Hence, gray scale effects can be achieved on this bi-level display (half-tone effects) in the same manner that pseudo gray scale effects have been achieved in EL and plasma displays.

The simplest method of achieving gray scale capability in bi-level display systems is the selective modulation of a fixed percentage of the pixels in a display.<sup>2</sup> Simple algorithms can be developed to control the average luminescence of an area, Fig. 86. By utilizing cells in pixel elements in groups of 4, 16 intensity levels can be achieved, Fig. 87.<sup>3</sup> These good quality gray scale images were generated using pulse width or drive current modulation techniques for plasma display applications.<sup>3</sup>

A technique called ordered dither can be used with standard bi-level systems to achieve reasonable gray scale images.<sup>4</sup> The process of ordered dither is similar to the half-tone process used in the printing industry. Simple algorithms with related hardware have been constructed to perform real-time TV, Fig. 88. The process of organized dither consists of comparing a multibit digitized image signal with an image position dependent set of thresholds and only turning on those corresponding panel cells where the threshold is exceeded. The subjective effect of continuous tone is achieved through the appropriate spatial density of on and off cells.

The pseudo-half-tone modulation scheme generated by the computer has also been used for liquid crystal displays, Fig. 89.<sup>5</sup>



Driving an electro-luminescent flat-panel display containing a quarter-million pixels need involve only 12 driver chips when each has 84 outputs. Actually small, square devices, they may bond directly to a 4 1/2-by-8-in. control board. The column drivers at the board's top and bottom handle alternate lines, as do the row drivers at its left and right. Data enters all the column drivers one row at a time.

From Electronic Design, April 6, 1984.

FIGURE IV-74

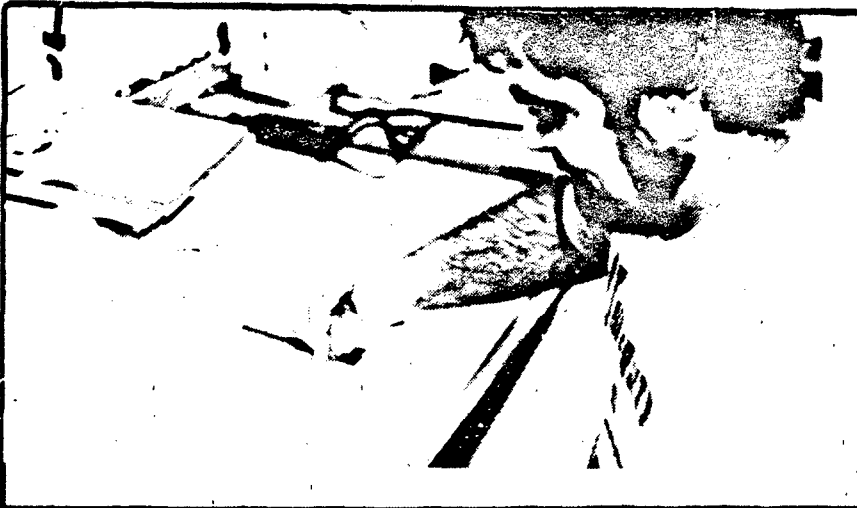
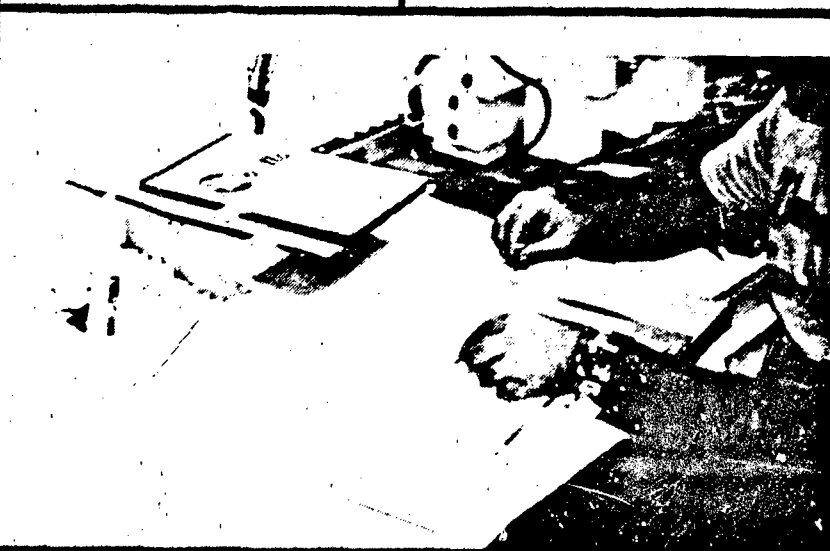
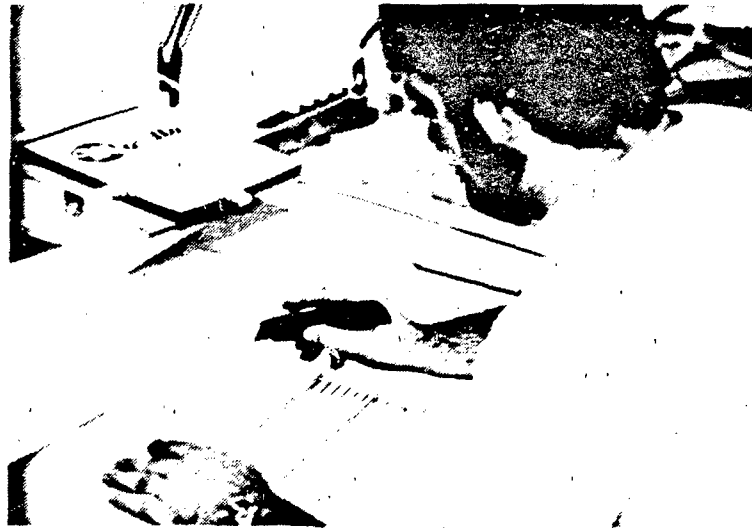


FIGURE IV-75

Steps in Construction  
of Modulation Plate



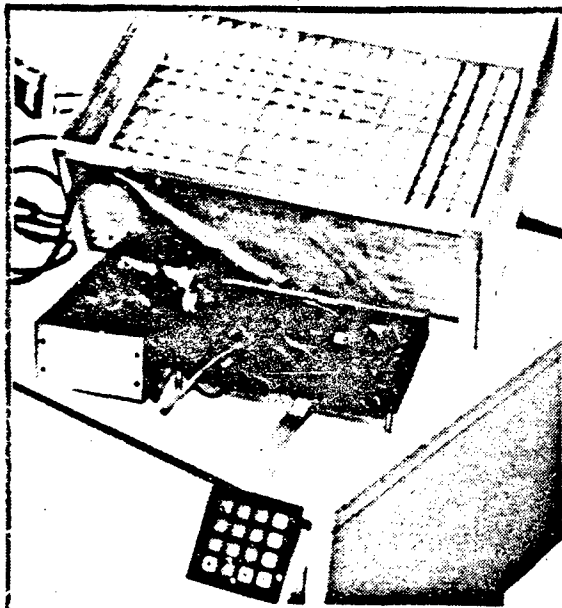


FIGURE IV-77

Completed Matrix  
Address System



FIGURE IV-76

PIXEL PLATE



FIGURE IV-78

Fabrication of Model  
of Modulation Plate

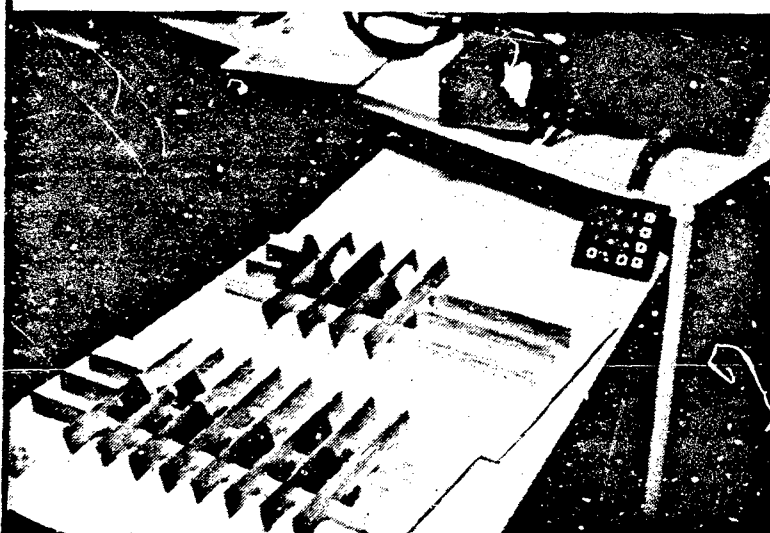
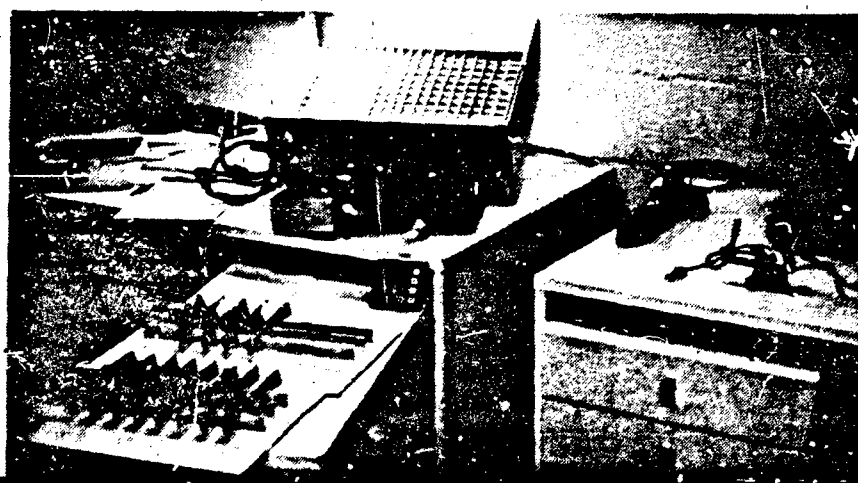


FIGURE IV-79

Enlarged Model  
of Modulation  
Plate for Color  
System



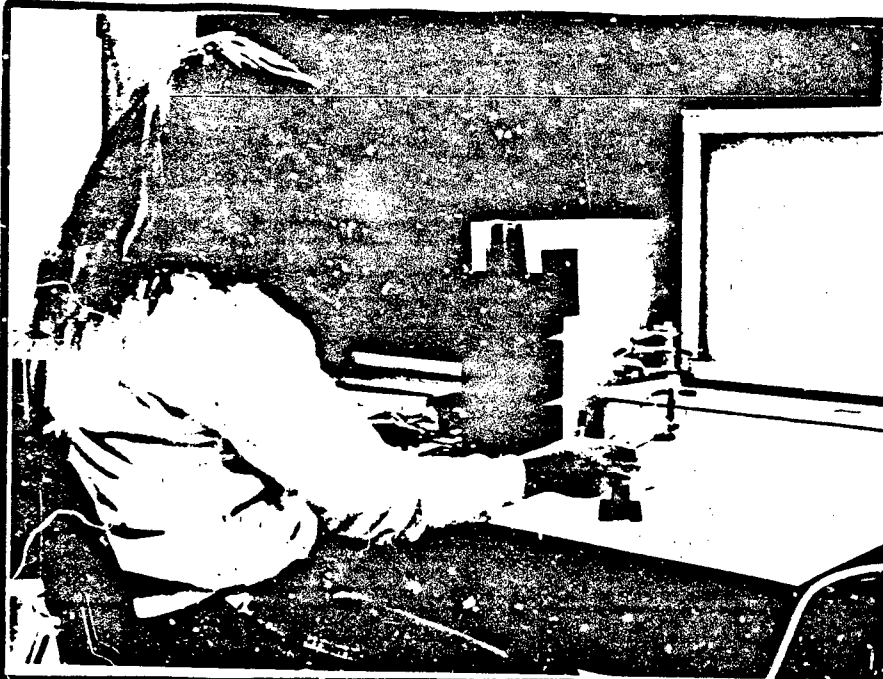


FIGURE IV-80

Four bimorph  
element for  
4x4 display.

FIGURE IV-81

Illuminated screen indicating  
typical pixel dimensions for  
experimental models.

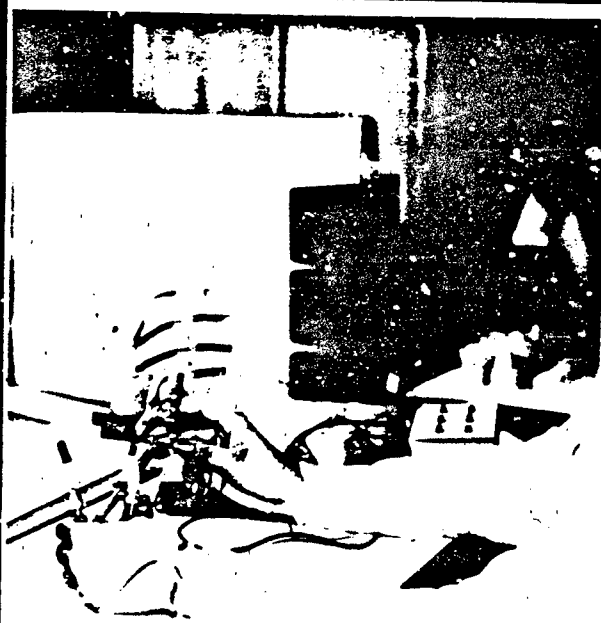


FIGURE IV-82

Fabrication of four bimorph  
element for 4x4 display.

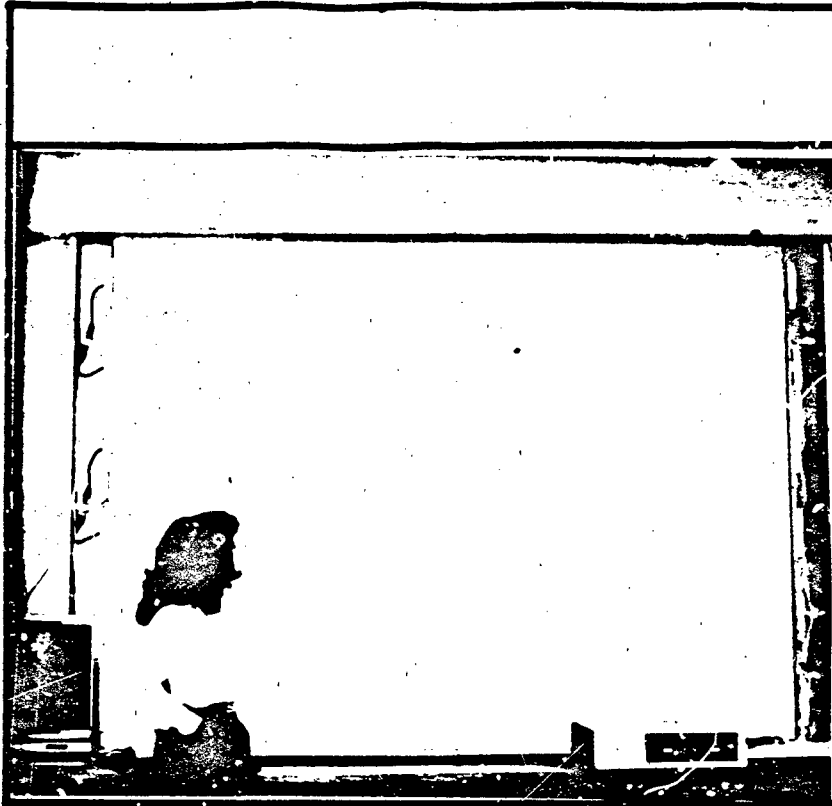


FIGURE IV-84

Full-scale pro-  
totype configu-  
ration

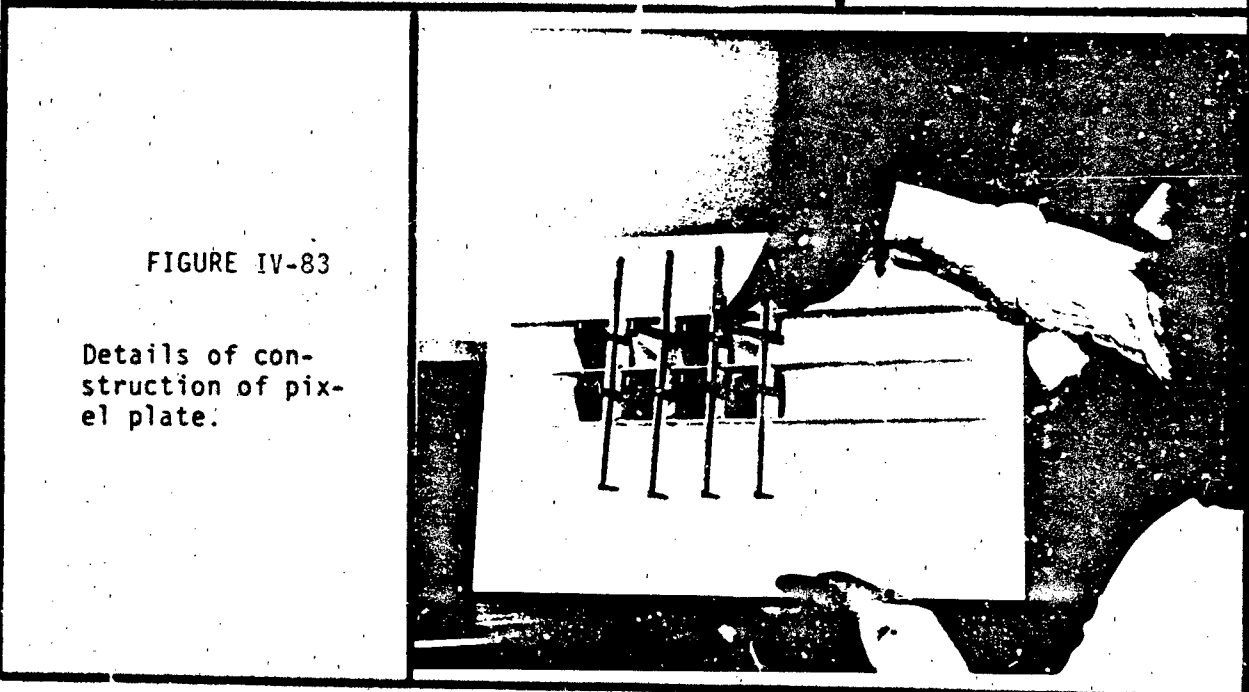
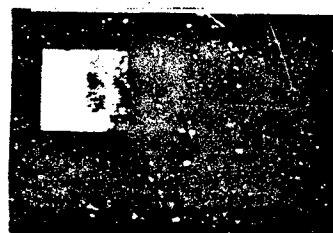
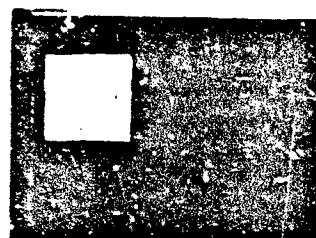
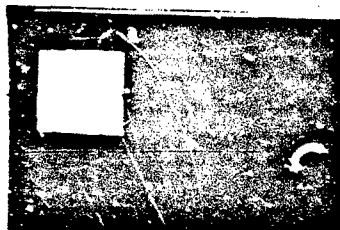


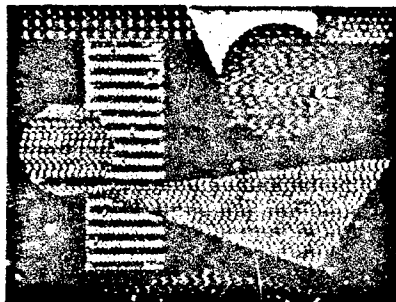
FIGURE IV-83

Details of con-  
struction of pix-  
el plate.



Gray scale produced by partial closure of  
pixel plate elements

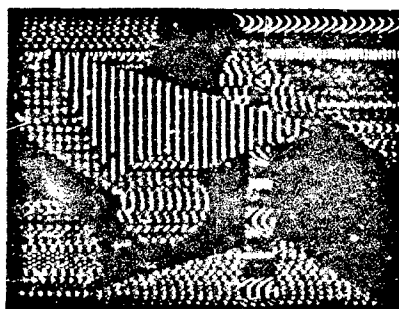
FIGURE IV-85



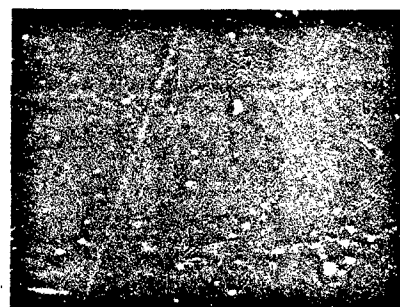
Solid figures with linear gray scale



Solid figures with various spatial gray scales



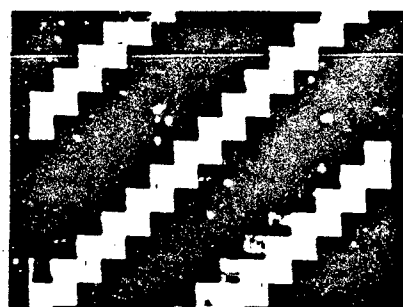
Solid figures at a linear gray scale of 1/12



Solid figures with spatial gray scale 1/8



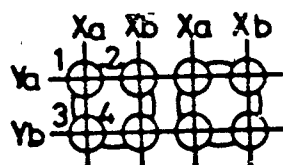
Shading example



The spatial gray scale

From Ref. 2

FIGURE IV-86



Configuration of a picture element.



16 intensity-level-pattern of brightness

From Ref. 3.

FIGURE IV-87



Original image. Digitized to 512 x 512 pels and 8 bits of intensity, displayed on CRT with equivalent resolution and grey scale.



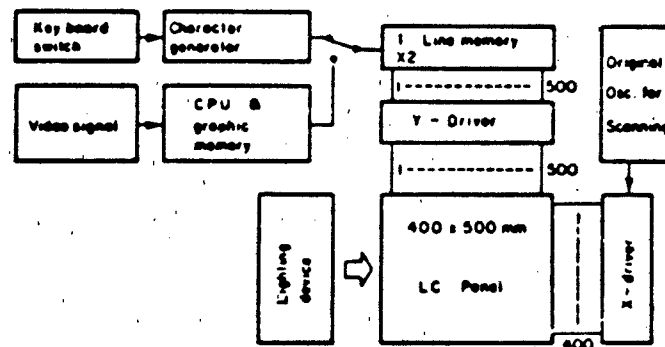
Dithered image, 16 x 16 dither matrix, displayed on 512-60 DIGIVUE panel.

From Ref. 4.

FIGURE IV-88



An image displayed on a large-scale liquid crystal display



Block diagram of a large-scale liquid crystal display

From Ref. 5.

FIGURE IV-89

These techniques can be employed to achieve a gray scale capability from the bi-level (black and white or color and white/black) MVD systems. Contrast ratios of from 12:1 to 25:1 can be achieved using the technique. Gray scale ranges approaches 16 can be achieved.\*

In the literature investigations that were carried out during the course of the program it was found that a number of investigators were also exploring the use of mechanical and electromechanical devices for display applications. Hornbeck<sup>6</sup> describes a deformable mirror device (DMD) employing an array of metalized polymer mirrors bonded to a silicon address circuit. The mirror deflection response time is 25 microseconds. The device is operated at about 30 volts with a cell size of 51 microns by 51 microns, Fig. 90.

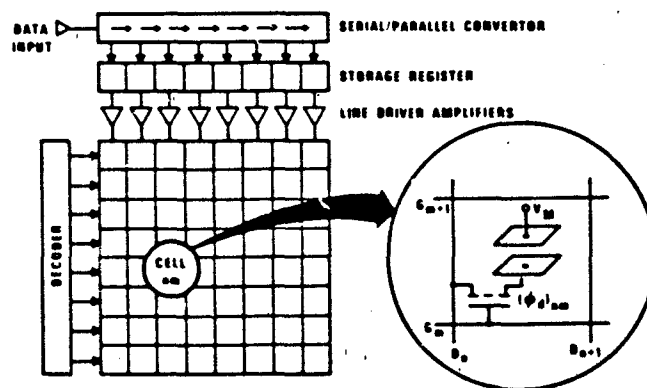
Display devices based on the rotation of thin micro-shutters held by straps over cavities in an electric field have been developed,<sup>7</sup> Fig. 91. The techniques used were based on the manufacturing techniques developed by the semiconductor industry. The shutters were 480 microns long and 80 microns wide. They were driven at working voltages of +/- 10 volts.

Between 1978 and 1981, Toda<sup>8</sup> developed several types of large area low resolution, individually addressed reflective displays which used the piezoelectric properties of PVDF. Fig. 92 shows the basic concept of a single pixel. A bi-colored vane, 1.5cm x 0.2cm is attached to a PVDF bimorph. When a 50v x 30ms pulse was applied to the bimorph, a different color was moved into the slot. He used 7 pixels to fabricate numeric displays. He also extended the concept to larger sized numerics. Toda and Osaka<sup>9</sup> observed that the deflection behavior of the experimental bimorphs remained essentially constant over ambient temperature ranges of -30°C to +40°C. Reliable operation (after performance stabilization at about 400 hours) was observed for periods of at least 1,000 hours.

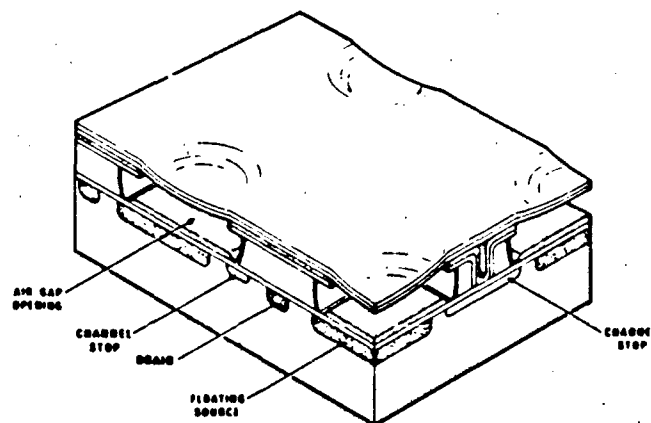
Lens systems have also been employed in displays. Tominga, et al, in 1982 described a lens plate used for a CRT rear projections system consisting of minute spheroidal lenses, Fig. 93.<sup>10</sup> When the rays were projected on the rear surface, parallel rays resulted. The transparent screen was formed using methylmethacrylate material and the lenses had spheroidal surfaces. The principle is similar to that proposed using the lens plates for the MVD system, Fig. 49.

Myoda, et al,<sup>11</sup> developed a large screen concept, Fig. 94, based on liquid crystal display (LCD) devices for use in indoor open spaces. The full-color display was constructed in modules with pixels at intervals of 7.2mm. The LCD panel was illuminated with fluorescent lamps, Fig. 95. Matsushita Electronic Components in Japan has recently developed a 3m x 12m flat-panel LCD display for video display in color.\* A control panel separated the video signal into the red, green, and blue color signals, converts these color signals from analog to digital form, and then routes the drive signals to the display panels. Light guides (pixel plates) were also used to improve brightness and mechanically connect panels to avoid connecting bar effects, Fig. 96.

\*Electronics Week, April 22, 1985. Note added in proof.



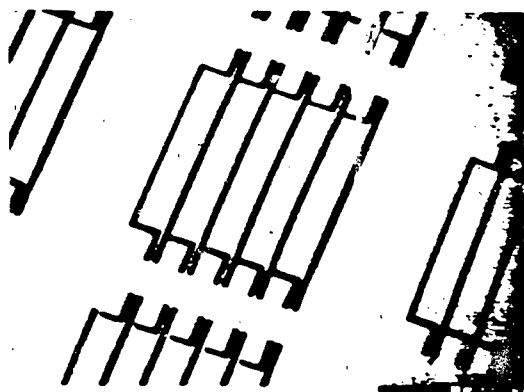
Deformable Mirror Device (DMD)  
Organization



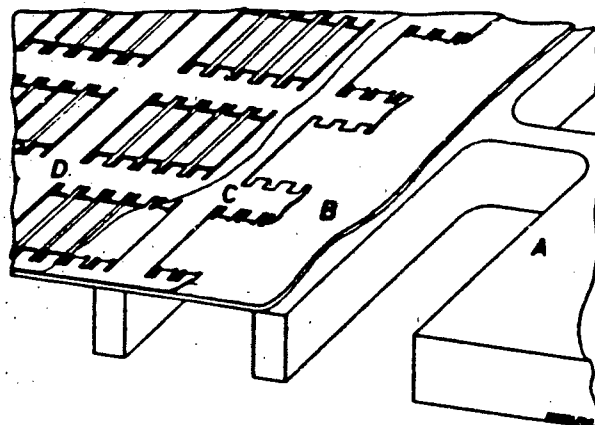
Perspective view of DMD

From Ref. 6.

FIGURE IV-90



Microphotograph showing groups of micro-shutters at rest.

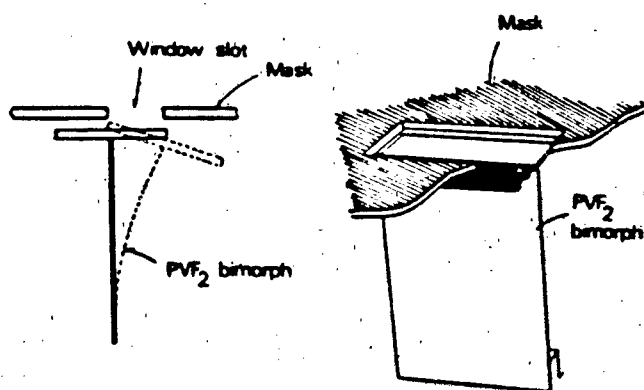


Schematic representation of the display layers:

- A : the supporting metal grid
- B : the textured plastic sheet
- C : the strengthening thick aluminum metallisation
- D : the shutter and strap geometries etched in the thin aluminum metallisation.

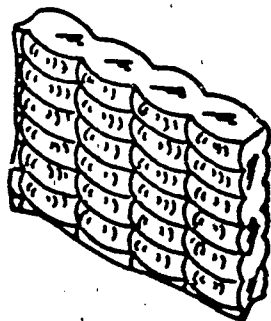
From Ref. 7.

FIGURE IV-91



From Ref. 8

FIGURE IV-92



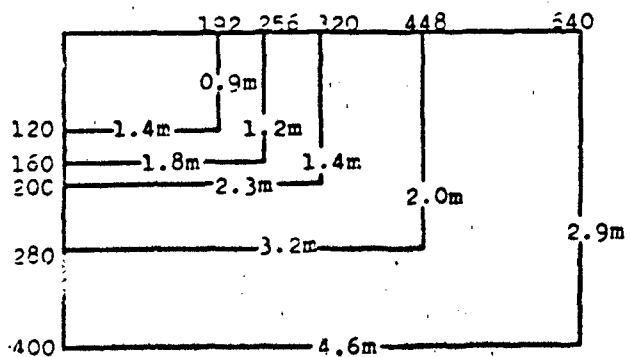
View of newly developed screen



Refraction of three primary color rays

Ref. 10.

FIGURE IV-93



\*Figures written at the outside of frames designate the number of pixels arranged to build up the screens.

Screen Module

From Ref. 11.

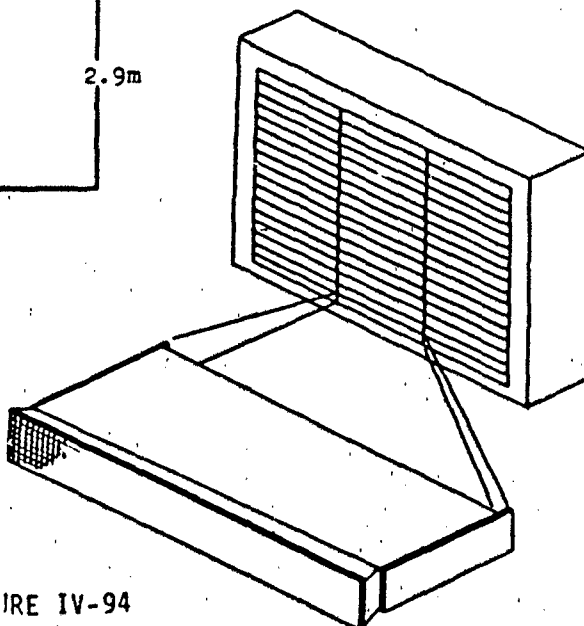
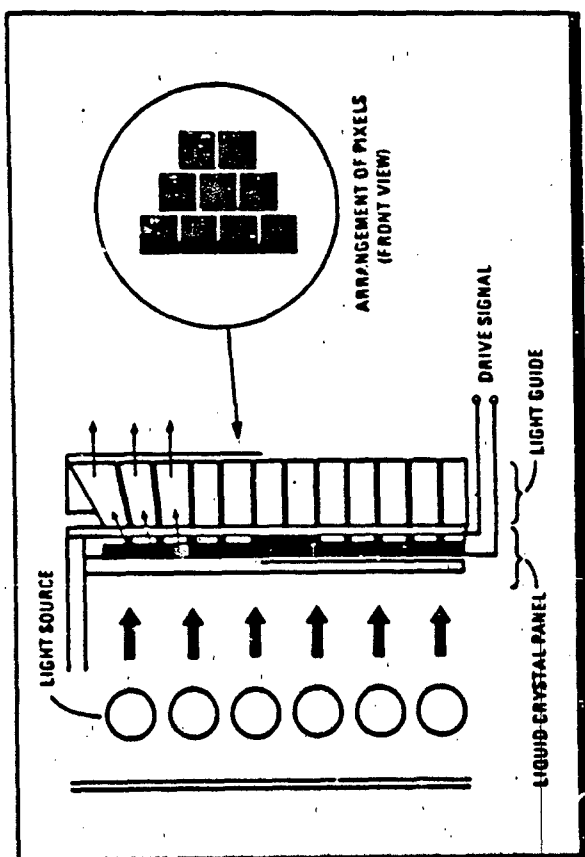


FIGURE IV-94



Use of fluorescent light source and pixel elements (light guides) in a large screen color LCD display.

From Ref. 11.

FIGURE IV-96

When large screen flat-panel displays are discussed using EL, LCD, or plasma technologies, panel sizes of approximately one-meter by one-meter are usually envisioned. As indicated in Fig. 97, this represents, essentially, the lower limit for MVD systems.

A technological ranking of displays from Electronic Business is shown in Fig. 98. The MVD technology can be compared with existing systems and projected systems as suggested in Fig. 97. Probably the major drawback of MVD systems is the susceptibility to shock and vibration since the thin films forming the basis for light modulation do not possess high stiffness. The displays formed using this technology will be primarily stationary and fixed in place. Currently, the cost of the PVDF film is also a constraining factor in the development of low cost displays. The basic film, before treatment is very inexpensive and increased demand will substantially lower the film cost. In the early development phase, pixels are essentially fabricated individually. Fabrication techniques can, however, be developed.

It is suggested that the MVD device technology might provide the basis for the first very large scale, flat-panel, full-color display, and that this technology could lead to the development of displays capable of satisfying the U.S. Army Corps of Engineers Engineer Topographic Laboratories requirement for large screen stationary topographic displays.

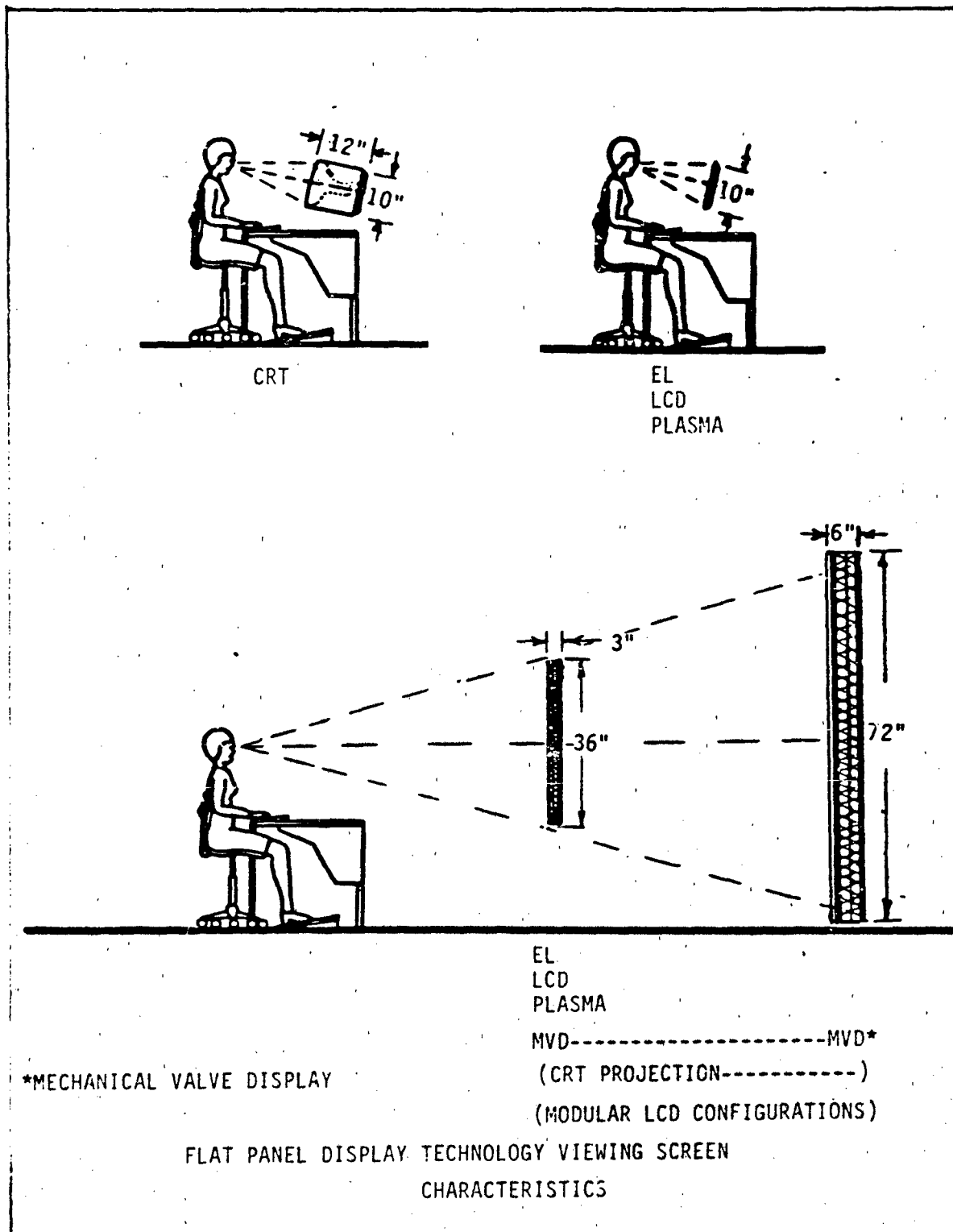


FIGURE IV-97

Technological ranking of displays*				
Attributes	CRT	Plasma	LCD	Electro-luminescent
Shape and operating characteristics				
Power consumption	Fair	Poor	Excellent	Fair-good
Screen size	Excellent	Good-excellent	Fair	Fair
Depth	Poor	Good	Excellent	Excellent
Weight	Poor	Fair-good	Excellent	Good
Ruggedness	Fair-good	Excellent	Excellent	Good-excellent
Operating temp. range	Good	Excellent	Fair-good	Excellent
Image quality				
Brightness	Excellent	Excellent	Fair-good	Excellent
Resolution	Good	Good	Fair-good	Good
Contrast	Good-excellent	Good	Fair	Good
Grey scale	Excellent	Fair	Poor-fair	Fair
Viewing angle	Excellent	Good-excellent	Poor-fair	Good
Color capability	Excellent	Poor	Poor-fair	Poor
Image stability	Fair	Excellent	Good-excellent	Excellent
Motion targeting	Good-excellent	Poor-fair	Fair	Poor-fair
Cost	Low	High	Low	Medium

Source: Arthur D. Little Inc.

\*Electronic Business, March 1984

Technological ranking	
Attributes	MVD*
Shape and operating characteristics	
Power consumption	Fair-Good
Screen size (for large display)	Excellent
Depth	Excellent
Weight	Good
Ruggedness	Poor
Operating temp. range	Good
Image quality	
Brightness	Excellent
Resolution	Good
Contrast	Good
Grey scale	Good
Viewing angle	Good
Color capability	Excellent
Image stability	Good
Motion targeting	Good
Cost	

\*Mechanical Valve Display

FIGURE IV-98

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APPENDIX B

GLOSSARY

## DEFINITIONS, ABBREVIATIONS, ACRONYMS, SYMBOLS

### 1. Symbols and definitions

PVDF - difluorethylene or vinylidene fluoride ( $\text{CH}_2=\text{CF}_2$ )

PZT - lead zirconate titanate

C - capacitance

$C_T$  - thermal capacitance

$C_V$  - specific heat

c - elastic modulus

$c_V$  - velocity of sound

$d_{31}$ ,  $d_{32}$ ,  $d_{33}$ ,  $d_h$ ,  $d_t$  - piezoelectric strain or charge constant

$e_{31}$ ,  $e_{32}$ ,  $e_{33}$  - piezoelectric stress or charge constant

G - thermal conductivity

$g_{31}$ ,  $g_{32}$ ,  $g_{33}$ ,  $g_h$ ,  $g_t$  - piezoelectric strain or voltage constant

$k_{31}$ ,  $k_{32}$ ,  $k_{33}$  - electromechanical coupling constant

$k_B$  - Boltzman's constant

p - pyroelectric coefficient

$s_{ij}$  - elastic compliance, mechanical deformation of film

l - length

w - width

t - thickness

Y - Young's modulus ( $s_{11}^E$ )<sup>-1</sup>

Q - electric charge

F - magnitude of the "tip" force of PVDF multimorph layers

x - displacement

W - watts

$\rho$  - mass density

$\mu$  - dipole moment

LCD - liquid crystal display

RAM - random access memories

CRT - electron beam scan technology

LED - light emitting diodes

EPID - electrophoretic image displays.

PROM - programable read only memory

EPROM - erase only programable read only memory

CMOS - complementary metal oxide semiconductor

BIMORPH DESIGN

### List of Symbols

A	Area of electrodes
C	Capacitance
$C_T$	Thermal Capacity
$C_V$	Specific Heat
D	Dielectric displacement
$D^*$	Normalized detectivity
E	Electric field
$F_0$	Force
G	Thermal conductivity
L	Length
P	Electric polarization
$P_T$	Thermal power
Q	Charge on the electrode
R	Amplitude reflection coefficient
$R_T$	Thermal impedance
S	Strain
T	Temperature
$T_g$	Glass transition temperature
V	Voltage across electrodes
X	Stress
Y	Young's modulus ( $= S_{ii}^{-1}$ )
$Z_a$	Acoustic impedance
$Z_e$	Electrical impedance
$Z_m$	Mechanical impedance

c	Elastic modulus
$c_v$	Velocity of sound
d	Piezoelectric strain or charge constant (d constant)
e	Piezoelectric stress or charge constant (e constant)
g	Piezoelectric strain or voltage constant (g constant)
h	Piezoelectric stress or voltage constant (h constant)
k	Electromechanical coupling constant
$k_b$	Boltzman's constant
p	Pyroelectric constant
s	Elastic compliance ( $s_{ij} = (c^{-1})_{ij}$ )
t	Thickness
w	Width
x,y,z	Cartesian coordinates
$\Delta$	increment from initial natural state
$\epsilon$	permittivity
$\epsilon_0$	permittivity of free space
$\eta$	thermal energy absorption
$\lambda$	wavelength
$\rho$	mass density
$\rho_R$	volume resistivity
$\rho_s$	surface resistivity
$\tau$	relaxation time
$\tau_E$	electrical time constant
$\tau_T$	thermal time constant
$\nu$	volume thermal expansion
$\omega$	angular frequency
$\tan \delta$	dielectric dissipation factor

Superscript     D, E, P, X, S, indicate these quantities are held constant

Subscripts     1,2,3 correspond with Cartesian coordinates  
                    x, y, z respectively

h     hydrostatic condition

t     thickness mode

## GLOSSARY OF TELEVISION TERMS

The field of television, is common with many specialized disciplines, has many technical, scientific, and slang terms that are used to describe equipment, methods, concepts, and phenomena associated with it. The following terms and expressions encompass a great many of those in common usage today.

**AMBIENT LIGHT LEVEL.** The intensity of light surrounding an object.

**APERTURE.** An opening that permits light, electrons, or other forms of radiation to pass through. In an electron gun, the aperture determines the size, and has an effect upon the shape, of the electron beam. In television optics, it is the effective diameter of the lens that controls the amount of light reaching the camera tube.

**APERTURE CORRECTION.** In television, a means whereby a video signal is electronically enhanced to increase image sharpness.

**APERTURE MASK.** A metal plate with accurately formed holes, placed close behind the phosphor-dot faceplate in a tricolor picture tube. It insures that each of the three electron beams excites only the desired phosphor dot. Also called a shadow mask.

**ASPECT RATIO.** The ratio of width to height for the frame of the televised picture. The U.S. standard is 4:3.

**BANDWIDTH.** The range of frequencies within which performance, with respect to some characteristic, falls within specific limits. (EIA).

**BEAM WIDTH.** Angular width of a beam, measured in azimuth.

**BLACK COMPRESSION.** The reduction in gain applied to a picture signal at those levels corresponding to dark areas in a picture, with respect to the gain at that level corresponding to the midrange light valve in the picture. (EIA). Reduces contrast in the low lights of the picture as seen on a monitor.

**BLACK LEVEL.** That level of the picture signal corresponding to the maximum limit of black peaks. (EIA)

**BLACK NEGATIVE.** Television picture signal in which the polarity of the voltage corresponding to black is negative with respect to that which corresponds to the white area of the picture tube.

**BLANKING.** The process of cutting off the electrons beam in a camera tube or picture tube during retrace.

**BLANKING LEVEL.** That level of a composite picture signal which separates the range containing picture information from the range containing synchronizing information. Note: The "setup" region is regarded as picture information. (EIA).

**BLANKING SIGNAL.** A wave constituted of recurrent pulses, related in time to the scanning process, used to effect blanking. (EIA).

**BRIGHTNESS.** The attribute of visual perception in accordance with which an area appears to emit more or less light. (EIA).

**CANDLEPOWER.** Refers to the amount of light in a given area. One foot-candle is the amount of light emitted by a standard candle at one foot distance. Average office or classroom lighting generally ranges from 25 to 75 foot-candles. Bright sunlight is approximately 10,000 foot-candles. The desirable light level in a television studio is generally a minimum of about 250 foot-candles

for monochrome and 400 foot-candles for color.

CHROMATIC ABERRATION. See "Aberration".

CHROMATICITY. The color quality of light that is defined by the wavelength (hue) and saturation. Chromaticity defines all the qualities of color except its brightness.

CHROMINANCE. A color term defining the hue and saturation of a color. Does not refer to brightness.

CHROMINANCE SIGNAL. The I and Q sidebands of the color subcarrier in a modulated color signal. These carry information relative to hue and saturation of colors but none relative to brightness.

CIRCLE OF CONFUSION. The image of a point source that appears as a circle of finite diameter because of the aberrations inherent in an optical system (including the eye).

COLOR BURST. In NTSC color, normally refers to a burst of approximately 8 or 9 cycles of 3.58-megahertz subcarrier on the back porch of the composite video signal. Serves as a color synchronizing signal to establish a frequency and phase reference for the chrominance signal.

COLOR DECODER. In color television reception, an apparatus for deriving the receiver primary signals from the color picture signals and the colorburst. (EIA).

COLOR ENCODER. A device that produces a NTSC color signal (encoded) from separate R, G, and B video inputs. May also generate the color burst. Also known as color modulator, and colorplexer.

COLOR PURITY. A term used in reference to the operation of a tricolor picture tube. It refers to the production of pure red, green, or blue illumination of the phosphor-dot faceplate.

COLOR SUBCARRIER. In NTSC color, the carrier whose modulation sidebands are added to the monochrome signal to convey color information; i.e., 3.579545 megahertz.

COLOR SUBCARRIER OSCILLATOR. A stable 3.58-megahertz (actually 3.579545 megahertz) oscillator used to generate the color subcarrier.

COMPATIBLE COLOR. The characteristic of a color video signal that makes it acceptable for use in a monochrome receiver.

COMPLEMENTARY COLOR. A color formed by subtracting a sample color from white light. For example, if red is subtracted, leaving blue and green, the complementary color is cyan (blue-green).

COMPOSITE PICTURE SIGNAL. The signal that results from combining a blanked picture signal with the sync signal. (EIA).

COMPRESSION. The reduction in gain at one level of a picture signal with respect to the gain at another level of the same signal. (EIA).

CONTRAST. The range of light and dark values in a picture, or the ratio between the maximum and minimum brightness values. (EIA). Sometimes expressed as contrast ratio.

CYAN. The complement of red (blue-green).

DEFINITION. The fidelity with which a televised image represents the original scene.

DEPTH OF FIELD. The "in focus" range of an optical system, measured from the distance behind an object to the distance ahead of an object where the apparent focus is maintained.

DETAIL. The smallest elements resolvable on a monitor display. Similar to resolution.

DETAIL CONTRAST. The ratio of the amplitude of video signal representing high frequency componenets with the amplitude representing the reference low-frequency component, usually expressed as a percentage at a particular line number. (EIA).

DIFFRACTION. The apparent deflection of rays of light as they pass by sharp edges, producing multicontrast, or multihued, bands of light when projected onto a surface.

FIELD. One of the equal parts into which a television frame is divided in an interlaced system of scanning. One vertical scan, containing many horizontal scanning lines, is generally termed a field.

FIELD FREQUENCY. The product of fram frequency multiplied by the number of fields contained in one frame. (EIA). The U.S. standard is 60 fields per second. Also called field repetition rate.

FIELD LENS. Lens used to effect the transfer of the image formed by an optical system.

FIELD OF VIEW. The solid angle that an optical system can see.

F/NUMBER. Relative aperture. Ratio of diameter to focal length of a lens or mirror.

FOCAL LENGTH. Distance from the principal point in a lens to the actual focal point.

FOCAL POINT. The point at which a lens or mirror will focus parallel light rays.

FOCUS. The point at which light rays or an electron beam form a minimum-size point or spot. Also, the action of bringing light ot electrons to a fine spot.

FOCUS CONTROL. A manual adjustment for bringing the electron beam of a camera pickup tube or picture tube to a minimum-size spot, producing the sharpest image.

FOOT-CANDLE. A unit of illuminance when the foot is taken as the unit of length. It is the illuminance on a surface one square foot in area on which there is a uniformly distributed flux of one lumen, or the illumination at a surface all points of which are at a distance of one foot from a uniform source of one candle. (EIA).

FOOT-LAMBERT. A unit of luminance equal to  $1/\pi$  candle per square foot, or to the uniform luminance of a perfectly diffusing surface emitting or reflecting light at the rate of one lumen per square foot. (EIA).

FRAME. The total area, occupied by the picture, which is scanned whilw the picture signal is not blanked. (EIA). Television in the United States commonly employs two interlaced fields per frame.

FRAME FREQUENCY. The number of times per second that the complete frame is scanned. The U.S. standard is 30 frames per second.

FREQUENCY INTERLACE. In color television, the method by which color and black and white sidebands signals are interwoven within the same channel bandwidth.

F/STOP. Refers to the speed or relative ability of a lens to pass light. It is calculated by dividing the focal length of the lens by its diameter.

GEOMETRIC DISTORTION. Any aberration that causes the reproduced picture to be geometrically dissimilar to the perspective plane projection of the original scene. (EIA).

GRAY SCALE. Variations of value from white, through shades of gray, to black on a television screen. The gradations approximate the tonal values of the original image picked up by the television camera.

HORIZONTAL BLANKING. The blanking signal at the end of each scanning line. (EIA). Allows horizontal retrace to occur unobserved.

HORIZONTAL INTERVAL. The period of time required to complete one horizontal scan and retrace.

HORIZONTAL RESOLUTION. The number of individual picture elements that can be distinguished in a horizontal scanning line within a distance equal to the picture height,

HORIZONTAL RETRACE. The return of the electron beam from the right to the left side of the raster after the scanning of one line. (EIA).

HUE. The dominant color of an object as determined by the wavelength of the emitted or reflected light. It is the redness, blueness, greenness, etc., of an object.

INCIDENT LIGHT. The light that falls directly on an object.

INDEX OF REFRACTION. The ratio of the velocity of light in a vacuum to the velocity of light in a refractive material for a particular wavelength of light.

INTERLACED SCANNING. A scanning process in which the distance from center to center of successively scanned lines is two or more times the nominal lines width, and in which the adjacent lines belong to different fields.

#### LENS SHAPES:

Plano-convex. One convex side, one flat side.

Double convex (biconvex). Both sides convex.

Plano-concave. One concave side, one flat side.

Double concave (biconcave). Both sides concave.

Meniscus. One convex side, one concave side.

LENS SPEED. Refers to the ability of a lens to pass light. A fast lens might be rated  $f/1.4$ ; a much slower lens might be designated as  $f/8$ . The larger the  $f$ /number, the slower the lens.

#### LIGHTING:

EYE LIGHT. A special source of illumination designed to effect desirable reflection from the eyes of a subject without substantially affecting the overall lighting condition.

FRESNEL. A special lens with concentric circle forms impressed in its front surface to focus spotlight beams for use in studio lighting. May be obtained in a variety of designs with restricted focusing from a 16-degree beam to a flood of some 70 degrees.

FILL LIGHT. Auxiliary illumination to lessen contrast range or to reduce shadows.

KEY LIGHT. The lightning effect indicating the direction of the major source of illumination of a scene.

SCOOP. A floodlight employed to illuminate large areas at close range.

SET LIGHT. Auxiliary illumination of the background or set, in addition to the lighting supplied for the major subjects or areas.

SIDE BACK-LIGHT. Off-center illumination behind the subject.

LUMEN. Unit of light flux. It is the power of light falling on 1 square meter of a hollow sphere of 1-meter radius at the center of which is a light source of 1 candlepower.

MATRIX (SWITCHER). A combination or array of electromechanical or electronic switches that route a number of signal sources to one or more destinations.

MEGAHERTZ (MHz). One million cycles per second.

MONOCHROME. Pertaining to black and white television systems, one chromaticity.

MONOCHROME SIGNAL. (1) In monochrome television, a signal wave for controlling the luminance values in that picture. (2) In color television, that part of the signal wave which has major control of the luminance values of the picture, whether displayed in color or in monochrome. (EIA).

MULTIPLEXER (OPTICAL). A specialized optical device that makes it possible to use a single television camera in conjunction with one or more motion picture projectors and/or slide projectors in a film chain.

NEGATIVE IMAGE. Refers to a picture signal having a polarity that is opposite to normal polarity and which results in a picture in which the white areas appear as black and viceversa. (EIA).

OBJECTIVE. The element or elements of an optical system that form(s) an image of the object.

OPTICAL AXIS. A straight line passing through the centers of the curved surfaces of a lens.

PEAK-to-PEAK VOLTAGE. The sum of the extreme negative and positive alternations of a signal.

PHOTOCONDUCTOR. A device in which electrical resistance varies in relationship with exposure to light.

PICTURE ELEMENT. Any segment of a scanning line, the dimension of which (along the line) is exactly equal to the nominal line width.

POLARITY OF PICTURE SIGNAL. The sense of the potential of a portion of the signal representing a dark area of a scene relative to the potential of a portion of the signal representing a light area. Polarity is stated as black negative or black positive. (EIA).

PREAMPLIFIER. An amplifier, the primary function of which is to raise the output of a low-level source to an intermediate level so that the signal may be further processed without appreciable degradation on the signal-to-noise ratio of the system. (EIA)

**PRIMARY COLORS.** Three colors wherein no mixture of any two can produce the third. In color television these are the additive primary colors, red, blue, and green.

**PROJECTION TELEVISION.** A unit composed of a high intensity picture tube and a series of mirrors and lenses arranged in such a manner as to project an enlarged television image.

**PULSE RISE TIME.** The interval between the instants at which the instantaneous amplitude first reaches specified lower and upper limits, namely 10 per cent and 90 per cent of the peak-pulse amplitude unless otherwise stated.

**RASTER.** A predetermined pattern of scanning lines which provides substantially uniform coverage of an area,

**REFERENCE BLACK LEVEL.** The picture signal level corresponding to the specified maximum limit for black peaks.

**REFERENCE WHITE LEVEL.** The picture signal level corresponding to the specified maximum limit for white peaks.

**RESOLUTION.** The details that can be distinguished on the television screen. Vertical resolution is a function of the number of scanning lines one sees on the screen. Horizontal resolution is a function of the number of intensity variations within each scanning line, and is generally variable according to the bandwidth of the system in use.

**RESOLUTION:**

**ANGULAR.** The angle subtended by the image of a point on the object.

**HORIZONTAL.** The amount of resolvable detail in the horizontal direction in a picture. It is usually expressed as the number of distant vertical lines, alternately black and white, that can be seen in a distance equal to the picture height. This information usually is derived by observation of the vertical wedge of a test pattern. A picture that is sharp and clear and shows small details has good or high resolution. If the picture is soft and blurred and small details are indistinct, it has poor or low resolution. Horizontal resolution depends upon the high-frequency amplitude and phase response of the pickup equipment, the transmission medium, and the picture monitor as well as the size of the scanning spots.

**PHOTOGRAPHIC.** The number of lines per inch or per millimeter which can be resolved by an optical system.

**VERTICAL.** The amount of resolvable detail in the vertical direction in a picture. It is usually expressed as the number of distinct horizontal lines, alternately black and white, that can be seen in a test pattern. The vertical resolution is fundamentally limited by the number of horizontal scanning lines per frame. Beyond this, vertical resolution depends on the size and shape of the scanning spots of the pickup equipment and picture monitor and does not depend upon the high-frequency response or bandwidth of the transmission medium or picture monitor.

**SATURATION:**

**IN COLOR DISPLAYS.** The degree to which a color is pure, undiluted with white light.

**IN AMPLIFIERS.** The point on the operational curve of an amplifier at which an increase in input amplitude will no longer result in an increase in amplitude at the output of an amplifier. An amplifier so overextended is

is said to be saturated.

SCANNING. Moving the electron beam of an pickup tube or a picture tube diagonally across the target or screen area of the CRT.

TEST PATTERN. A chart especially prepared for checking overall performance of a television system. It contains various combinations of lines and geometric shapes. The camera is focused on the chart, and the pattern is viewed at the monitor for fidelity.

VERTICAL RETRACE. The return of the electron beam to the top of the picture tube screen or the pickup tube target at the completion of the field scan.

VIDEO. A term pertaining to the bandwidth and spectrum position of the signal resulting from television scanning. In current usage, video means a bandwidth in the order of megahertz, and a spectrum position that goes with a dc carrier.

VIDEO AMPLIFIER. A wideband amplifier for the picture signals.

VIDEO SIGNAL (NONCOMPOSITE). The picture signal. A signal containing visual information and horizontal and vertical blanking. See "Composite Video Signal."

VTR/VCR. Video tape recorder, (Video Cassette Recorder).

WAVEFORM MONITOR. An oscilloscope designed especially for viewing the waveform of a video signal.

Y SIGNAL. A signal transmitted in color television containing brightness information. This signal produces a black and white picture on a standard monochrome receiver. In a color picture, it supplies fine detail and brightness information.

## Electrical Conversion Table

### Capacitance

<u>parameter</u>	<u>unit</u>	<u>conversion factor</u>
capacitance	F(farad)	1 F = 1 Coul/V

### Conductance

conductance	S(siemens)	1 S = 1 Amp/V = 1/Ω
		1 mho = 1 S

### Current

Current	Amp(Ampere)	1 Amp = 1 Coul.sec
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### Electric Charge

electric charge	C(coulomb)	1 C = 1 Amp-s 1 C = $6.242 \times 10^{18}$ electronic charges 1 C = $1.306 \times 10^{-5}$ Faradays
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### Electric Potential

electric potential	V(volt)	1 V = 1W/Amp
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### Piezoelectric Strain Coefficient

Unit for  $d_{nm}$  =  $10^{-9}$  statcoulomb/dyne

=  $1/3 \times 10^{-12}$  coulomb/newton

=  $10^{-9}$  cm/statvolt

=  $1/3 \times 10^{-12}$  meter/volt

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**END**

**FILMED**

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**DTIC**